Wide-field Slitless Spectroscopy from Space: Unique Constraints on Galaxy Evolution from Cosmic Dusk to Dawn

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Why slitless spectroscopy?

• Wide-field slitless surveys at $z=1-2$:
  • Large, uniform, ~unbiased samples
  • Spatially-resolved line diagnostics @ HST resolution
  • $\Delta z/(1+z) \sim 0.003$: large scale structure & stacking
• Spectroscopic constraints at cosmic dawn
• Promising future prospects
NEAR-INFRARED SPECTROSCOPIC SURVEY WITH THE HUBBLE SPACE TELESCOPE

ACS specs:
• 2-4 orbit coverage
• 0.55 to 1.0 um
• 40 A/pix

WFC3 specs
• 2 orbit coverage
• 1.1 to 1.65 um
• 46.5 A/pix

Brammer et al., 2012
NEAR-INFRARED SPECTROSCOPIC SURVEY WITH THE HUBBLE SPACE TELESCOPE

mosaics: F140W 3D-HST
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GOODS-S catalog, photometric redshifts, F140W $< 24$.

$N \sim 5,000$ objects

Skelton et al., 2014
GOODS-S catalog, grism+photometry redshifts, \( F140W < 24. \)

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GOODS-S catalog, grism+photometry redshifts, $F_{140W} < 24$.

$N \sim 5,000$ objects

$H\alpha$ $N \sim 1000$

$H\beta$ $N \sim 100$

$[OIII]$ $N \sim 400$

$[OII]$ $N \sim 100$

Momcheva et al., 2015
Automated extraction enables robust quantitative measurements for \textit{10s of thousands of galaxies}\footnote{Momcheva+2015}. 

\begin{itemize}
\item Balmer/4000Å break (abs.)
\item Hγ
\item Hδ
\item [OIII]
\item Hα+[NII]
\item [SII]
\item [OII]
\item HeI
\item λ_{rest} / \mu m
\item N × 10^3 \quad (z, H_{160} < 24)
\end{itemize}
Highly complete spectroscopic coverage allows detailed study of correlation and evolution of galaxy properties.

Momcheva+2015
CANDELS+3D-HST: High-z SDSS

- >200,000 catalog entries
- 147 different bands, including available medium and narrow bands
- few % phot_z’s
- EAZY photometric z’s
- FAST SFR, M*, sSFR, Av, tau, age
- Morphological parameters
- Rest-frame colors (Skelton et al., 2014)

- Grism spectra for ~20,000 objects to F140W<24. (~10^5 to F140W<26.)
- Grism + photometry redshifts, dz/(1+z) ~0.003
- Emission line fluxes, EQW (Momcheva et al., 2015)

http://3dhst.astro.yale.edu
https://archive.stsci.edu/prepds/3d-hst/
Science Highlights
The Bimodality of Galaxy Populations

Fumagalli et al., in prep.
Where do stars form?

0.7<z<1.5: ~33% of all cosmic star formation

Nelson et al. (2012)
Where do stars form?

0.7 < z < 1.5:
- star formation occurs in disks
- disks are building inside out

Nelson et al., 2015
Where do stars form?

- Look at stacks on, above and below the star-forming sequence
- Elevated (suppressed) at all radii above (below) the SF sequence
  - e.g., no evidence for central starbursts

![Diagram showing radial distribution of star formation](image_url)
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(Aside: Balmer Decrement)

- Get Hα + Hβ in a narrow redshift slice around z~1.3

Price+2014
Where do stars form?

\[
\begin{array}{ccc}
\text{H}_\alpha & 9.0 < \log(M) < 9.2 & 9.2 < \log(M) < 9.8 & 9.8 < \log(M) < 11.0 \\
\text{H}_\beta & & & \\
\end{array}
\]
Where do stars form?

The fully corrected H$\alpha$ and H$\beta$ profiles, in units of erg s$^{-1}$ cm$^{-2}$ arcsec$^{-2}$, are shown in Figure 2. We can reliably trace H$\alpha$ out to $\sim$6 kpc, and the $\sim$3 × fainter H$\beta$ out to $\sim$3 kpc; at larger radii the error in the measurement is more than half of the measured flux. At low masses, the H$\alpha$ and H$\beta$ surface brightness profiles are nearly exponential. As mass increases, the H$\alpha$ emission grows more centrally concentrated while the H$\beta$ becomes less centrally concentrated than exponential. This is the central result of this Letter: with increasing stellar mass, galaxies become increasingly more dust obscured toward their centers.

Figure 2 also shows the effect of assuming different quantities of stellar absorption (shaded regions). These profiles were derived by artificially changing the absorption line equivalent width in the best-fitting 2D EAzY model, increasing and decreasing it by half.

A potential concern in this analysis is that by stacking small galaxies with high attenuation and large galaxies with low attenuation, we could infer a radial dust gradient where on an individual galaxy basis, there is none. To test this, we remove all compact galaxies with sizes more than 0.1 and 0.3 dex below the size-mass relation from the stack. In both cases, the qualitative trends remain unchanged, which means that the gradients are real, and not a byproduct of stacking a heterogeneous sample. Another concern is that normalizing galaxies by their H$F_{140W}$ flux biases the stacks toward galaxies with high H$\alpha$ and H$\beta$ equivalent widths. If galaxies with high equivalent widths have preferentially low dust attenuation, this analysis could underestimate the true dust attenuation at the median mass of the stacks. However, normalizing galaxies by their H$\alpha$ flux gives a qualitatively similar measurement, albeit with significantly lower signal-to-noise.

3. RADIAL GRADIENTS IN DUST ATTENUATION

The increase in the slope and normalization of the Balmer decrement with $M$ implies a corresponding increase in the slope and normalization of the dust attenuation. We derive the dust attenuation toward H$\alpha$ as follows. The increase of the Balmer decrement over the intrinsic value can be expressed in terms of a Balmer color excess:

$$ E_{H 2.5} = \log \frac{H_\alpha}{H_\beta} - \frac{1}{2} $$

Figure 2. Average radial surface brightness profiles of H$\alpha$ (red), H$\beta$ (blue), and H$\alpha$/H$\beta$ (the Balmer decrement, black) in galaxies as a function of $M$. Random uncertainties are shown by bootstrap error bars representing 68% confidence intervals derived by resampling the data with different realizations. Systematic uncertainties derived by artificially increasing and decreasing the absorption line equivalent widths by half are shown by shaded regions. The dashed line shows ($H_\alpha$/H$\beta$)$_{int}$, the "intrinsic" line ratio in the absence of dust attenuation. We can reliably measure the average Balmer decrement gradients in galaxies at $z \sim 1.4$ to nearly 3 kpc. With the Balmer decrement tracing dust attenuation toward H$\II$ regions, this figure shows that with increasing stellar mass, galaxies become increasingly dust-obscured toward their centers.
Where do stars form?

Nelson+2016

- Now see more of an enhancement in (massive) galaxy centers: building bulges with in-situ star formation?
Extended Low Ionization Emission-Line Regions at $z \approx 0.9$

- Spatially-resolved emission line diagnostics
- First evidence of LIERs at high $z$

Hviding et al., in prep.
Cosmic Dawn
Cosmic Dawn

- Place constraints on emission line strength for GOODS-N z~10 candidates (Oesch+2014, 2016)
Cosmic Dawn

- Deep grism spectra of the $z \approx 12$ candidate UDFj-39546284 revealed a faint emission line that could explain all of its broadband flux in $H_{160} \rightarrow$ more likely $z \approx 2.2$ (Brammer+2013)
Cosmic Dawn

- Place constraints on emission line strength for GOODS-N z~10 candidates (Oesch+2014, 2016)
Cosmic Dawn

- Overall $5.5\sigma$ at $\lambda > 1.47$ $\mu$m
- Break factor of $>3.1$ ($2\sigma$, 500Å)
  - (Maximally old BC03 model at $z=2.7$ a factor of $<2.7$ defined the same way)
- Best-fit redshift of combined spectra + photometry: $z=11.1 \pm 0.1$
Future Prospects
New capabilities with slitless spectroscopy: archival work

- 4x G141 area
- Joint G102+G141
- Deep pointings at multiple angles
- Heterogeneous supporting data (but always WFC3 imaging)
- Standardized analysis
- Cycle 24 Legacy Archival Program (AR-14553)
New capabilities with slitless spectroscopy: JWST

Capabilities science capabilities with dramatic improvements in:

- Sensitivity
- Resolution
- Bandpass
New capabilities with slitless spectroscopy: JWST

- **JWST NIRISS+FGS**
  - Big telescope! 0.065” pixels, ~WFC3/IR FOV
  - Two grisms rotated by 90°, $R=150$ (like WFC3/G141)
  - Bandpass limiting by crossed filters, \(0.9 – 2.2 \text{ \mu m}\)

Simulation by G. Brammer
https://github.com/gbrammer/grizli/
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- JWST NIRCAM Long Wave
  - Big telescope! 0.065” pixels, 2 detectors, FOV~4.4’ x 2.2’
  - Two grisms rotated by 90°, $R=1500!$
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New capabilities with slitless spectroscopy:  **WFIRST**

- **WFIRST** GRS grism
  - 0.28 deg$^2$ at a shot, 2400 deg$^2$ (!) High Latitude Survey (z for BAO, RSD, public survey)
  - 2.4m telescope (≈HST)
  - 1.3–1.9 µm, $R = 4 \times G141$ (e.g., just resolves H$\alpha$, [NII])

Simulation by G. Brammer
https://github.com/gbrammer/grizli/
WFIRST: 0.28 deg$^2$ / pointing, 2400 deg$^2$ total
New capabilities with slitless spectroscopy

WFC3/IR
- $H\alpha$
- $H\beta$, $[O\text{III}]$
- $[O\text{II}]$

JWST
- NIRISS, NIRCam
- Deep, $H\alpha \ z>5$, $[O\text{III}] \ z>6$

Euclid
- Shallow, $10^4 \ deg^2$

WFIRST
- $\approx 3D$-HST, $2K \ deg^2$
Conclusions

- Slitless grism surveys offer highly complete spectroscopic resource for galaxy evolution studies.
- Slitless nature of the spectra presents data analysis challenges, but with significant benefits (e.g., continuum depth, completeness, spatial resolution).
- Lessons, science, and targets from current HST grism programs will help pave the way for upcoming space missions (JWST, EUCLID, WFIRST).