The VANDELS survey: Dust attenuation in star-forming galaxies at $z = 3 - 4$

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Introduction

- Extinction: individual sight-lines, absorption + scattering out of the line-of-sight, related to the size distribution and composition of the dust grains
- Attenuation: extended sources, extinction + scattering back into the line-of-sight, a strong dependence on the dust geometry
- Main complication: the intrinsic shape of a galaxy SED is less well constrained

Some key questions on attenuation curve:
- changes with galaxy properties?
- redshift evolution?
- the presence/absence of the 2175 Å UV bump?
Method 1

- Use an independent indicator to identify galaxies that are more, or less, affected by dust, compare their observed SEDs
- Advantage: not having to assume the shape of a dust-free SED
- Disadvantage: sensitive to the total-to-selective attenuation law, rather than the attenuation law directly
Method 2

- Assume/construct the underlying intrinsic SED of all sources, compare the observed SEDs with the intrinsic SED
- E.g., Scoville et al. 2015
- Advantage: directly probe the wavelength dependence of the attenuation curve
- Disadvantage: suffers from an increasing systematic errors related to the choice of the intrinsic SED
- The problems will be mitigated somewhat at high redshifts where star-formation histories are predicted to become self similar across the galaxy population
Sample selection

VANDELS Survey:

- ESO spectroscopic survey
- \( N \approx 2000 \) galaxies at \( 1.0 < z < 7.0 \) in CDFS and UDS
- Instrument: VLT/VIMOS
- \( R \approx 600, \lambda = 4800 – 10000 \) Å
- To be completed in January 2018

Selecting from 1502 VANDELS spectra:

- \( I_{\text{AB}} \leq 27.5 \) and \( H_{\text{AB}} \leq 27 \) (original VANDELS selection criteria)
- the most secure redshift of \( 3.0 \leq z \leq 4.0 \) (242)
- \( \log(M_*/M_\odot) \leq 10.6 \) (236)

Final sample:

- \( 1.6 \times 10^8 \leq M_*/M_\odot < 4.0 \times 10^{10}, \langle M_* \rangle = 4.5 \times 10^9 \ M_\odot \)
- \( \langle z \rangle = 3.49 \)
Photometry

Four samples: CDFS-HST, CDFS-GROUND, UDS-HST, and UDS-GROUND

- CDFS-HST and UDS-HST: $\sim 50\%$, within CANDELS regions (CDFS and UDS), deep optical to NIR HST imaging, Spitzer/IRAC observations
- $\lambda = 0.5 - 8.0 \ \mu m$, rest-frame UV to NIR SED out to $\lambda_{\text{rest}} \sim 2.0 \ \mu m$
- CDFS-GROUND and UDS-GROUND: $\sim 50\%$, relies on predominantly ground-based imaging
- $\lambda$ only extends out the K-band ($\sim 2.2 \ \mu m$), rest-frame UV to optical SED out to $\lambda_{\text{rest}} \sim 0.6 \ \mu m$
Two publicly-available SED-fitting codes:

- **EAZY** (Brammer et al. 2008)
- linear combinations of a limited standard template set
- fixing $z$ to spectroscopic redshift measured from the VANDELS spectra
- **LePhare** (Illert et al. 2008)
- determine $M_*$
- Setting: constant SFH, BC03, Calzetti et al. (2000) attenuation curve
- Final observed SEDs: averaged the best-fitting LePhare and EAZY SEDs
A homogeneous SED shape

Assumption: all galaxies in the sample have the same intrinsic UV to optical SED shape

- First Billion Years (FiBY) simulation
- Sample: 628 galaxies with $8.2 \leq \log(M/M_\odot) \leq 10.6$ at $z = 4$
- Based on the similarity of SFHs, and the narrow range in metallicity, it is reasonable to assume that the underlying SED shape will be similar across all masses.
Intrinsic SEDs:

Construct intrinsic SEDs:

- Assign each star particle an instantaneous starburst SPS model based on age and metallicity
- Sum up SEDs of all individual star particles for each galaxy
- Pair each VANDELS spectrum with FiBY galaxy based on mass
- Stack matched SEDs of FiBY galaxies
Intrinsic SEDs:

Construct intrinsic SEDs:

- **BPASSv2 + CLOUDY**
- **BPASSv2-100bin**: binary star evolution + an IMF cutoff of 100 $M_\odot$
- **BPASSv2-100**: single-star evolution + an IMF cutoff of 100 $M_\odot$
- **BPASSv2-300bin**: binary star evolution + an IMF cutoff of 300 $M_\odot$
- **BPASSv2-300**: single-star evolution + an IMF cutoff of 300 $M_\odot$
- **S99-v00-z***: constant SFH + Starburst99 + 100 Myr + $Z_* = 0.002(0.008)$
Fitting method

Basic formula:

\[ f_{\lambda, \text{obs}} = \phi f_{\lambda, \text{int}} e^{-\tau_{\lambda}} \]

\[ A_{\lambda} = 1.086 \tau_{\lambda} \]

\[ 1.086 \times \ln(f_{\lambda, \text{int}} / f_{\lambda, \text{obs}}) = A_{\lambda} - A_{V} \]

Adopting a second-order polynomial as a function of \( x = 1/\lambda \) for \( A_{\lambda} \):

\[ A_{\lambda} = a_{0} x + a_{1} x^{2} \]

\[ 1.086 \times \ln(f_{\lambda, \text{int}} / f_{\lambda, \text{obs}}) = a_{0} x + a_{1} x^{2} - A_{V} \]

\[ R_{V} = \frac{A_{V}}{A_{B} - A_{V}} \]

\[ k_{\lambda} = \frac{A_{\lambda} R_{V}}{A_{V}} \]
Wavelength windows for fitting

Wavelength pixels used to fit:

- an estimated nebular contribution of < 10%
- free from stellar absorption/emission features
An example fit

\[ 1.086 \ln \left( \frac{F_i}{F_0} \right) \]

\[ \lambda^{-1} / \mu m^{-1} \]

\[ 0.00 \]
\[ 0.25 \]
\[ 0.50 \]
\[ 0.75 \]
\[ 1.00 \]
\[ 1.25 \]
\[ 1.50 \]
\[ 1.75 \]
\[ 2.00 \]

\[ A_\lambda / A_V \]

Calzetti
SMC
Reddy+ 2015
Charlot+Fall 2000
Simple Simulation

- generated $1000 \ M_*$ within $8.2 \leq \log(M_*/M_{\odot}) \leq 10.6$
- assigned $A_V$ using the $A_V - M_*$ relation for a Calzetti law from McLure et al. (2017a)
- FiBY-BPASSv2-100bin template + nebular component
- perturbed flux assuming a 20% error

Using the defined wavelength regions, it is possible to recover the underlying Calzetti law and the input $A_V - M_*$ relation.
Average shape of the attenuation curve

- Failed fit: when observed SED was bluer than the intrinsic SED
- $f_{\text{failed}} < 5\%$ for half of the templates
- The majority of attenuation curves are shallow and Calzetti-like in shape.
$A_V - M_\star$ relation

- McLure et al. (2017a): 8407 galaxies at $2 < z < 3$
- S99-v00-z008, FiBY-BPASSv2 binary star templates: excellent agreement with both the McLure et al. (2017a) data and the empirical relation for a Calzetti dust law at $\log(M_\star/M_\odot) > 9.5$.
- S99-v00-z002, FiBY-BPASSv2 single-star templates: incompatible with the McLure et al. (2017a) data
$A_V - M_*$ relation

- $M_*$ is a good proxy for attenuation.
- The $A_V - M_*$ relation for normal star-forming galaxies with $\log(M_*/M_\odot) > 9.5$ does not evolve between $z = 0$ to $z \sim 5$.
Parameterization of the attenuation curve

Taking FiBY-BPASSv2-300bin as fiducial intrinsic SED template:

\[
\frac{A_\lambda}{A_V} = \frac{0.587}{\lambda} - \frac{0.020}{\lambda^2}, \quad 0.12 < \lambda < 0.63 \ \mu m
\]

\[
k_\lambda = \frac{2.454}{\lambda} - \frac{0.084}{\lambda^2}
\]

\[R_V = 4.18 \pm 0.29\]

The results are fully consistent with the Calzetti attenuation law.
• constructed stacked intrinsic SED from FiBY with log(M_*/M) < 9.0
• a steepening of the attenuation curve at the lowest M_*
• remain consistent with the Calzetti law within 1σ, and rule out SMC-like curve at > 1σ
Evidence for a 2175 Å UV bump?

\[ A_\lambda = \frac{A_V}{4.05} [k(\lambda)_{\text{Calzetti}} + D(\lambda)] \]

\[ D(\lambda) = \frac{E_b(\lambda \Delta \lambda)^2}{(\lambda^2 - \lambda_0^2) + (\lambda \Delta \lambda)^2} \]

where \( \lambda_0 = 2175 \, \text{Å} \), \( \Delta \lambda = 350 \, \text{Å} \), \( A_V = 0.8 \).

- 122 galaxies at \( 3.0 < z < 3.5 \)
- robustly rule out the presence of a strong UV bump with \( E_b > 1.0 \)
- a weak 2175 Å UV bump feature with \( E_b \sim 1 \)
## Summary

- The intrinsic shape of the UVoptical SED of SFGs at $z = 3 - 4$ is approximately constant across $8.2 < \log(M_* / M_\odot) < 10.6$.
- The average attenuation curve shapes are consistent with a grey Calzetti-like attenuation law within $\pm 1\sigma$.
- No evidence is found for a steep SMC-like attenuation law.
- A subset of the intrinsic template sets yield results which are consistent with the observed data, and with the $A_V - M_*$ relation predicted for a Calzetti-like attenuation law.
- The $A_V - M_*$ relation does not evolve over $0 < z < 5$.
- $R_V = 4.18 \pm 0.29$ (the original Calzetti value of $R_V = 4.05 \pm 0.80$).
- Tentative evidence for steeper attenuation curve shapes at $\log(M_* / M_\odot) < 9.0$ is found.
- A weak 2175 Å UV bump in the average attenuation curve at $z \sim 3$ is suggested by spectra of 122 galaxies at $3.0 < z < 3.5$. 