MOSDEF: Measurements of Balmer Decrements and the Dust Attenuation Curve at High Redshift
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Understanding Nebular Emission in High-Redshift Galaxies; Carnegie, 17 July 2015
Importance of the Dust “Curve” for High-z Galaxies

Calzetti (2011)

Important input to SED fitting
Needed to infer dust-corrected SFRs
Encodes info on the dust/stars geometry

...combining UV and optical diagnostics of HII regions
Recent High-Z Constraints on the Dust Curve

- Noll+09
- Buat+11,12
- Kriek & Conroy 2013
- Scoville+15

Based on photometry, spectroscopy (in UV/optical), and/or comparison to stellar templates
Proxies for Dust at High-z

• UV Slope: sensitive to age, metallicity, and star-formation history; measurement can be complicated by presence of 2175 Å absorption feature

• Far-IR Measurements: only available for more luminous and dusty galaxies (ALMA helping this to some extent)

  ➔ need tracers that are less sensitive to stellar population parameters (age and star-formation history), probe star formation on short timescales, and can be measured for individual typical star-forming galaxies at high redshift

BALMER DECREMENTS
(e.g., Calzetti et al. 1994, Kennicutt et al. 2009, Groves et al. 2012, etc…)
MOSFIRE Deep Evolution Field (MOSDEF) Survey

- Conducted using MOSFIRE on Keck (47 nights)
- MOS near-IR spectroscopy covering important nebular emission lines at 1.4<z<3.8

Transformative survey:

(1) H band-selected rest-optical spectroscopy covering strongest em/abs features with high resolution to characterize gaseous/stellar contents of galaxies
(2) large sample of objects (~1500) spanning full range of galaxy properties
(3) multiple redshifts to enable evolutionary studies

Kriek et al. (2015)
Sampling of “Typical” Star-Forming Galaxies at z~2

Shivaei et al. (2015)

Reddy & Steidel (2009)
Balmer Decrement Measurements

\[ \tau_b \equiv \ln \left( \frac{H\alpha/H\beta}{2.86} \right) \]

224 star-forming galaxies at \( z_{\text{spec}} = 1.36 - 2.59 \)
Calculating the Attenuation Curve…

Ratios of Composites

\[-9.60 \leq \log_{10}[\text{sSFR/yr}^{-1}] < -8.84\]

\[\langle \tau_b \rangle = 0.000\]

\[N = 46\]

\[\langle z \rangle = 2.04\]

\[-9.60 \leq \log_{10}[\text{sSFR/yr}^{-1}] < -8.84\]

\[\langle \tau_b \rangle = 0.088\]

\[N = 20\]

\[\langle z \rangle = 1.95\]

\[-8.84 \leq \log_{10}[\text{sSFR/yr}^{-1}] < -8.00\]

\[\langle \tau_b \rangle = 0.065\]

\[N = 29\]

\[\langle z \rangle = 2.11\]

\[-8.84 \leq \log_{10}[\text{sSFR/yr}^{-1}] < -8.00\]

\[\langle \tau_b \rangle = 0.292\]

\[N = 29\]

\[\langle z \rangle = 2.15\]

\[-8.84 \leq \log_{10}[\text{sSFR/yr}^{-1}] < -8.00\]

\[\langle \tau_b \rangle = 0.582\]

\[N = 29\]

\[\langle z \rangle = 2.13\]
Calculating the Attenuation Curve...

Normalization ($R_V$)

Renormalized so that $f_{Q_{\text{eff}}}(\lambda \rightarrow 2.85 \, \mu \text{m}) = 0$

Systematic uncertainties of $\Delta R_V \approx 0.4$

Normalized so that $f[Q_{\text{eff}}(B) - Q_{\text{eff}}(B)] = 1$

$\log[\text{sSFR/yr}^{-1}] = -9.60$ to $-8.84$

$\log[\text{sSFR/yr}^{-1}] = -8.84$ to $-8.00$

Calzetti+94
Comparison to other common curves

Similar in shape (and normalization) to SMC at $\lambda > 2500$ Å
Similar in shape (but lower normalization) than Calzetti at $\lambda < 2500$ Å
Implications for SFR(SED) and $M^*$

$\approx 20\%$ lower SFRs with new curve

$\Delta \log(M^*/M_\odot) = 0.16 \text{ dex}$
Color Excesses of the Ionized Gas vs. Stellar Continuum

Higher attenuation towards lines-of-sight to massive stars

(e.g., Fanelli et al. 1988, Calzetti et al. 1994, Mas-Hesse & Kunth 1999, Kreckel et al. 2013)
Color Excesses of the Ionized Gas vs. Stellar Continuum

\[ E(B-V)_{\text{gas}} = \frac{2.5}{k(H\beta) - k(H\alpha)} \log_{10} \left( \frac{H\alpha/H\beta}{2.86} \right) \]

Assumes Cardelli+89 (Galactic) extinction curve
A Possible Physical Interpretation

Locally...ionizing stars found in parent birth clouds
A Possible Physical Interpretation

At high-z: stars of all masses are attenuated by same amount, with larger contribution of dust-enshrouded SF at higher SFRs.

“Low” SFR dominates the UV/optical continuum.

“High” SFR dominates the nebular line/bolometric luminosities.
Implications for SFRs from the UV or SED-fitting

UV/SED-based SFRs *underpredict* total SFR above ≈ 20 M$_\odot$/yr
Similar “Saturation” seen with IR vs UV-based SFRs

Reddy et al. (2010)
Similar “Saturation” seen with IR vs UV-based SFRs

Reddy et al. (2010)

Reddy+10

Saturation of UV luminosity around $L^*$ (UV)
Future Work

• Incorporate mid- and far-IR data

• Larger sample will enable studies of stellar attenuation curve as a function of other galaxy properties (e.g., SFR)

• Relationship between attenuation curve shape/normalization and resolved color maps

• Multiple Balmer emission lines
Conclusions

• Large sample of Balmer decrements aids in calculating the attenuation curve relevant for the stellar continuum.

• Attenuation curve found here is similar to SMC at longer wavelengths ($\lambda > 2500$ Å), and similar in shape, but with different normalization, than Calzetti+00.

• New curve implies SFR $\approx$20% lower, and log M* that are 0.16 dex lower, than those obtained with the Calzetti relation.

• Difference in the color excess (and total attenuation) of the ionized gas and stellar continuum correlates strongly with sSFR and SFR, with higher SFR galaxies exhibiting the largest differences.

• Data suggest a physical interpretation where galaxies consist of moderately reddened stellar population that dominated the UV through near-IR continuum, and a second, dustier population, that begins to dominate the line and bolometric luminosities at higher SFRs.

Extra Slides
Balmer Decrement Measurements

\[ \tau_b \equiv \ln \left( \frac{H\alpha/H\beta}{2.86} \right) \]

224 star-forming galaxies at \( z_{\text{spec}} = 1.36 - 2.59 \)

“Mild” Correlation between UV slope and \( \tau_b \)
Calculating the Attenuation Curve

Ratios of Composites

Limit to Galaxies of Similar Spectral Shapes

Spectral Shape

Dustiness
Effects of Star Formation History

- “sequence” of $\beta$ vs. $\tau_b$
- are A stars contributing to near-UV flux?

unlikely…
Effects of Metallicity?

Range of metallicity implies $\Delta \beta_{\text{int}} \approx 0.2$
Slit Losses
Dependence of the Difference in *Color Excess* on SFR

Dependence of the Difference in *Total Attenuation* on SFR
Excess UV Absorption at 2175 Å?

Binned by $E(B-V)$

Marginal ($3\sigma$) significance
Implications

SFR(SED) and SFR(UV) may underpredict total SFR at even “modest” levels

Appropriate attenuation curve to use for HII regions? Gray at low SFR, MW/SMC at high SFR?
Observed SFR(Hα)/SFR(UV) vs. SFR(Hα) (M_☉ yr^(-1)) - Cardelli