The Spectral Energy Distribution of Galaxies
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What can the UV SED tell us about primitive galaxies?

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Abstract. We use the full SED of a well observed dwarf galaxy, I Zw 18, to evaluate what inferences can be made about very high-redshift galaxies from their UV SED's alone.

Keywords. galaxies: evolution, dwarf, individual (I Zw 18), high-redshift, stellar content

1. Introduction

The ultraviolet spectral energy distribution (SED) is most often described by a power-law index, β, as in $F_\lambda = \lambda^\beta$, so the "bluer" the UV continuum, the more negative the value of β. Originally defined by Calzetti *et al.* (1994), the slope of the UV continuum has been used as a measure of extinction in star-forming galaxies, particularly after Meurer *et al.* (1999) showed that β is related to the infrared excess seen in galaxies. More recently, it has been used to characterize very high-redshift galaxies discovered with Hubble's Wide Field Camera 3 (WFC3), not only to estimate dust extinction but to infer other physical properties as well (e.g. Bouwens *et al.* 2010, Finkelstein *et al.* 2010).

In fact, the UV SED has become the basis of our knowledge about very high-redshift galaxies. In a just-released study of 2000 z = 4–7 galaxies observed by Hubble's ACS and WFC3 cameras, Bouwens *et al.* (2011) found that the rest-frame UV color as given by β becomes systematically bluer towards fainter UV luminosities at all redshifts between z = 4 and z = 7. In addition, the rest-frame UV colors of galaxies at a given UV luminosity get slightly bluer with increasing redshift. They argue that dust extinction (rather than stellar age, nebular emission, etc.) is the main driver for the trends they see.

These are impressive, exciting results! Nevertheless, as illustrated in §2, a single parameter like β cannot yield three independent physical parameters: age, metallicity, and dust extinction. So, in §3, we will explore the beta method using the blue compact dwarf (BCD) galaxy, I Zw 18, as a test case. I Zw 18 is a very low metallicity dwarf galaxy ($12+\log O/H = 7.2$). It is arguably the best local analogue to very high-redshift galaxies (Thuan 2008). I Zw 18 has been well observed from x-rays to the radio, so we can use its full SED to evaluate inferences made from the UV SED alone.

2. The UV-continuum slope parameter, β

The UV slope parameter is sensitive to many factors. Here, we describe the sensitivity of β to the stellar parameters and defer to the next section its sensitivity to gas and dust. Figure 1 shows how β changes with stellar age (i.e. the duration of star formation) and metallicity. The values of β in this figure were derived from model spectra calculated with Geneva evolutionary models (Lejeune & Schaerer 2001) and Castelli & Kurucz' (2004) grid of stellar spectra. It shows that stellar age and metallicity are degenerate: a galaxy of a given β can be young and metal-rich, or it can be older and more metal-poor.

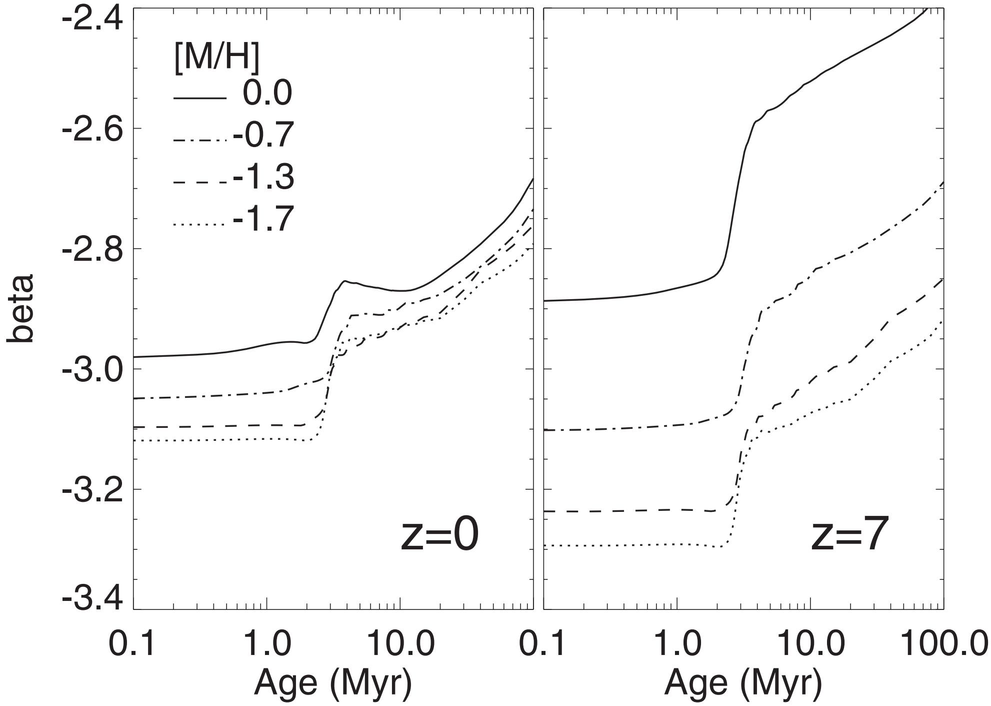

Figure 1. Variation of β with continuing star-formation (CSF) age and metallicity, [M/H], for model galaxies at z = 0 (left) measured over the wavelength range, $\lambda \sim$ 1270-1710 Å; and for z = 7 galaxies (right) observed by WFC3 at $\lambda_{\rm rest} \sim$ 1500-2000 Å.

However, we can say that a galaxy with a very blue UV continuum (large negative β) must be both very metal-poor and young (and have little to no dust extinction).

Figure 1 also shows that β depends on the rest-frame spectral region of the flux measurements. The beta method assumes that the stellar SED can be described by a power law, which is only appropriate if the UV SED follows a Rayleaigh-Jeans law. In fact, the UV SED of a young stellar population shows curvature on a log-log plot, with the slope of the SED flattening towards shorter wavelengths. Hence, it is essential to calibrate the beta method at the rest-frame spectral region where the flux measurements are made.

UV-faint galaxies at z = 7, which are the bluest galaxies in the WFC3 high-redshift sample, have $\beta = -2.7$ (Bouwens *et al.* 2011). Our studies of the northwest ionizing star cluster in I Zw 18 (Heap *et al.*, in preparation) suggest a stellar CSF age of 10-15 Myr and a metallicity, [M/H] = −1.7. Thus, the stellar component should have a $\beta = -2.9$, but its observed value (corrected for foreground reddening) is $\beta = -2.4$. The redder observed UV color may be due to our neglect of possible UV flux contributions from old stars ($\geqslant$ 1 Gyr) in the outskirts of I Zw 18 (Aloisi *et al.* 2007, Contreres Ramos *et al.* 2011). More likely, it is due to nebular continuum emission and/or dust absorption, a topic we take up in the next section.

3. UV SED vs. Full SED

The full SED of a star-forming galaxy is obviously better than a small segment, but not simply because more is better. The real advantage of a full SED is that it reveals important components of a galaxy that are not noticeable in the UV where young, massive stars are the dominant flux contributor. Figure 2 illustrates this point by showing the observed SED of I Zw 18 compared to models computed with Cloudy (Ferland *et al.* 1998). The model assumes a young massive star cluster at the center of a giant HİI region, which in turn, is surrounded by a H I cloud. The figure shows how different components of a galaxy are prominent in different spectral regions: hot, massive stars are the dominant contributor to the UV flux; nebular emission becomes stronger toward longer wavelengths and exceeds the stellar emission at $\geqslant 1\mu$; and dust emission is dominant in the thermal infrared. It suggests that nebular emission and dust absorption, which both work to redden the UV spectrum, must be involved in flattening the UV continuum of I Zw 18.

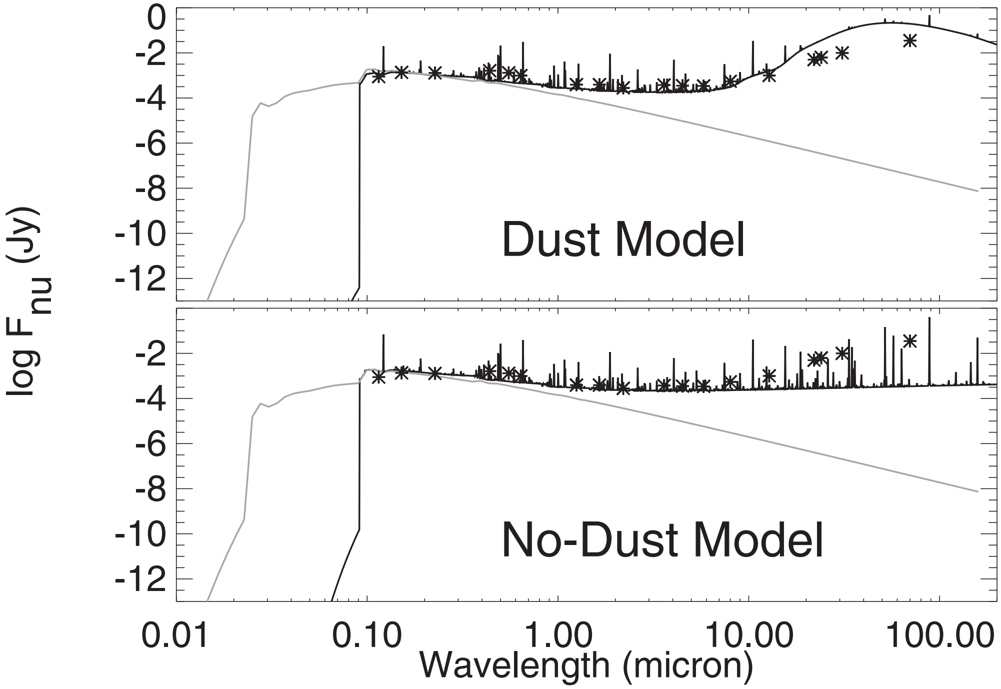

Figure 2. Observed and model SED's for I Zw 18. The observed data (asterisks) were taken from NASA's Extragalactic Database (NED). The model stellar SED is shown as a gray line; the Cloudy model SED (stars+gas+dust), as the solid black line.

Figure 3 compares a model UV SED from Cloudy to the UV spectrum of I Zw 18-NW obtained by Hubble's Cosmic Origins Spectrograph (COS). It shows that nebular emission is indeed present but at a low level. A weak nebular continuum flux is in line with other evidence that a significant fraction of stellar H-ionizing photons escapes the H II region (Dufour & Hester 1990; Pequignot's 2008). And although the surrounding H I cloud has a high H I column density, $N_{HI} = 2.2 \times 10^{21}$ cm^{-2}, it is "clumpy and irregular" (van Zee *et al.* 2006), so some ionizing photons may escape I Zw 18 altogether. Spitzer/MIPS imagery of I Zw 18 shows that 70μ dust emission follows the H I contours of 21-cm emission (Herrera *et al.* 2010), so the UV SED is likely flattened by extinction by dust produced by older stars in the extensive H I cloud.

In conclusion, the full SED of local galaxies like I Zw 18 is essential for revealing all the components and processes involved in making the UV SED of low-metallicity galaxies. The complexity of even dwarf galaxies, however, warns us to be careful in using them to interpret the radiation of very high-redshift galaxies.

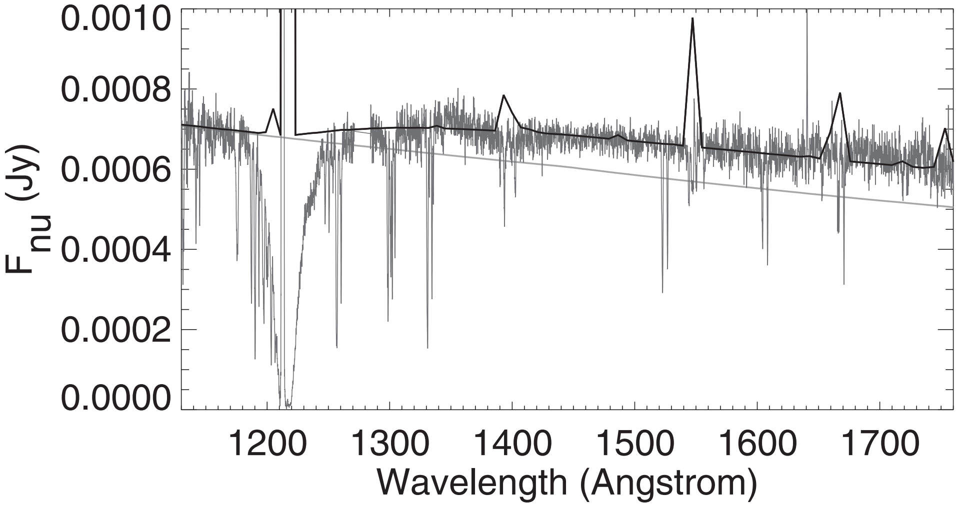

Figure 3. Comparison of the COS spectrum of I Zw 18 with our model stellar spectrum (gray) and Cloudy spectrum with coarse sampling (black).

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