The Universe at High Redshift

Pre-1995, there were only a few high-redshift galaxies at $z > 1$ known. Most of the ones that were known were giant radio galaxies.

Recall that high-redshift galaxies are faint:

$$ F = \frac{L}{4\pi D_L^2} $$

$D_L(z=1) = 6.6 \text{ Gpc}$

$D_L(z=2) = 15.5 \text{ Gpc}$

Galaxy at $z=2$ is $-5 \log[ D_L(z=1) / D_L(z=2) ] = 2 \text{ mag}$ fainter.

Most $z \sim 2$ galaxies will have $R > 23.5 \text{ mag}$. But, most galaxies with $R < 24.5 \text{ mag}$ will be at $z < 2$. How do you find high-redshift galaxies?
**K and E Corrections**

K-corrections are the method to convert between an observed bandpass \( R \) of a galaxy at a redshift \( z \) and a rest-frame bandpass \( Q \).

\[
m_R = M_Q + DM(z) + K_{QR}(z) - 5 \log h,\]

E-corrections are the method to correct for evolution in a galaxies stellar population (if you compare two ellipticals at \( z=0 \) and \( z=1 \), the one at \( z=0 \) has had \( \sim 8 \) Gyr years to evolve its stars).

In general:

\[
K(z) = + \left[ 2.5 \log(1 + z) + 2.5 \log \frac{\int_0^\infty E(\frac{\lambda}{1+z}, t_0) S(\lambda) d\lambda}{\int_0^\infty E(\frac{\lambda}{1+z}, t_0) S(\lambda) d\lambda} \right]
\]

\[
E(z) = + 2.5 \log \frac{\int_0^\infty E(\frac{\lambda}{1+z}, t_0) S(\lambda) d\lambda}{\int_0^\infty E(\frac{\lambda}{1+z}, t_1) S(\lambda) d\lambda}
\]

Where \( E(\lambda, t) \) is the spectral energy distribution of a stellar population at wavelength \( \lambda \) and age \( t \). \( S(\lambda) \) is the transmission curve of the filter (and \( S \) need not be the same in the numerator and denominator of these equations !!).
## K and E Corrections

B.M. Poggianti: $K$ and evolutionary corrections from UV to IR

### Table 1. Colours of the models of age 15 Gyr

<table>
<thead>
<tr>
<th></th>
<th>$(U - B)$</th>
<th>$(B - V)$</th>
<th>$(V - R)$</th>
<th>$(R - I)$</th>
<th>$(V - J)$</th>
<th>$(V - H)$</th>
<th>$(V - K)$</th>
<th>$(J - H)$</th>
<th>$(J - K)$</th>
<th>$(H - K)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>El1</td>
<td>0.53</td>
<td>0.95</td>
<td>0.76</td>
<td>0.67</td>
<td>2.25</td>
<td>2.95</td>
<td>3.23</td>
<td>0.71</td>
<td>0.98</td>
<td>0.28</td>
</tr>
<tr>
<td>El2</td>
<td>0.45</td>
<td>0.91</td>
<td>0.71</td>
<td>0.60</td>
<td>2.02</td>
<td>2.65</td>
<td>2.90</td>
<td>0.63</td>
<td>0.87</td>
<td>0.25</td>
</tr>
<tr>
<td>El3</td>
<td>0.37</td>
<td>0.86</td>
<td>0.67</td>
<td>0.54</td>
<td>1.86</td>
<td>2.42</td>
<td>2.65</td>
<td>0.57</td>
<td>0.79</td>
<td>0.22</td>
</tr>
<tr>
<td>Sa</td>
<td>0.33</td>
<td>0.85</td>
<td>0.69</td>
<td>0.60</td>
<td>2.01</td>
<td>2.65</td>
<td>2.90</td>
<td>0.64</td>
<td>0.89</td>
<td>0.25</td>
</tr>
<tr>
<td>Sb</td>
<td>0.21</td>
<td>0.77</td>
<td>0.66</td>
<td>0.58</td>
<td>1.95</td>
<td>2.57</td>
<td>2.82</td>
<td>0.63</td>
<td>0.87</td>
<td>0.24</td>
</tr>
<tr>
<td>Sc</td>
<td>0.02</td>
<td>0.63</td>
<td>0.59</td>
<td>0.54</td>
<td>1.80</td>
<td>2.40</td>
<td>2.63</td>
<td>0.60</td>
<td>0.83</td>
<td>0.23</td>
</tr>
<tr>
<td>Sd</td>
<td>-0.09</td>
<td>0.52</td>
<td>0.53</td>
<td>0.48</td>
<td>1.62</td>
<td>2.18</td>
<td>2.40</td>
<td>0.56</td>
<td>0.78</td>
<td>0.22</td>
</tr>
</tbody>
</table>

Colors of empirical galaxy SEDs from Poggianti 1997.
K and E Corrections

Lanzetta et al. 1997

$z=0$

Lanzetta et al. 1997
K and E Corrections

\[ z = 1 \]

\[ \log f_{\lambda} \]

\[ \lambda \text{ (Å)} \]

\[ z = 1 \]

Tuesday, November 27, 12
K and E Corrections

E and K corrections to derive observed V-K colors

Poggianti 1997
Steidel et al. 1995

Lyman Break Galaxy Selection

J114816.64+525150.3 \( z = 6.43 \) Keck/ESI

Ly\(\alpha\)

Ly\(\beta\)+OVI

Lyman Limit

NV

Ol+Sill

CIV abs

Steidel et al. 1995
Lyman Break Galaxy Selection

Therefore, any source at high redshift will have its flux attenuated by neutral hydrogen at wavelengths shortward of Lyman-\(\alpha\) rest-frame (see Madau 1995; Madau et al. 1996).

\[
\langle f(v_{\text{obs}}) \rangle = \frac{(1 + z_{\text{em}}) L(v_{\text{em}})}{4\pi d_L^2} \langle e^{-\tau} \rangle,
\]

where \(v_{\text{obs}} = v_{\text{em}}/(1 + z_{\text{em}})\), \(d_L\) is the luminosity distance and the average transmission over all lines of sight is (assuming poisson-distributed clouds).

\[
\langle e^{-\tau} \rangle = \exp\left\{ \int_{0}^{z_{\text{em}}} \int \frac{\partial^2 N}{\partial N_{H_1} \partial z} [1 - e^{-\tau_c}] dN_{H_1} dz \right\}.
\]

where \(\tau_c\) is the optical depth through an individual cloud and the double partial derivative is the redshift and column density distribution of absorbers along the line of sight.

The “effective” optical depth of a clumpy medium can be defined as

\[
\tau_{\text{eff}} = -\ln(\langle e^{-\tau} \rangle)
\]
Lyman Break Galaxy Selection

For wavelengths between Ly\(\beta\) and Ly\(\alpha\) in the frame of the emission source, the continuum of the galaxy is attenuated by combined blanketing of many Ly\(\alpha\) forest absorption lines, with effective opacity

\[
\tau_{\text{eff}} = 0.0036 \left( \frac{\lambda_{\text{obs}}}{\lambda_{\alpha}} \right)^{3.46},
\]

(Press, Rybicki, & Schneider 1993), or roughly \(\sim 1\) mag of attenuation for a galaxy at \(z>4\) at wavelengths shortward of 6000 Å.

For wavelengths shorter than Ly\(\beta\) in the rest frame of the source line blanketing comes from higher order lines in the Lyman series. A numerical analysis of the curve of growth gives

\[
\tau_{\text{eff}} = \sum_{j=2,i} A_j \left( \frac{\lambda_{\text{obs}}}{\lambda_j} \right)^{3.46}, \quad A_j = (1.7 \times 10^{-3}, 1.2 \times 10^{-3}, 9.3 \times 10^{-4})
\]

for Ly\(\beta\), Ly\(\gamma\), and Ly\(\delta\), respectively.
Below the Lyman limit ($\lambda_L = 912 \text{ Å}$) in the rest-frame of the source the effective optical depth along the line of sight is given as an approximation by Madau:

$$
\tau_{\text{eff}} = 0.25x_c^3(x_{\text{em}}^{0.46} - x_c^{0.46}) + 9.4x_c^{1.5}(x_{\text{em}}^{0.18} - x_c^{0.18}) \\
- 0.7x_c^3(x_c^{-1.32} - x_{\text{em}}^{-1.32}) - 0.023(x_{\text{em}}^{1.68} - x_c^{1.68}),
$$

where $x_c = (\lambda_{\text{obs}}/\lambda_L)$ for $\lambda_{\text{obs}} > \lambda_L$, and $x_{\text{em}} = 1 + z_{\text{em}}$.

Broad-band colors of distant galaxies will be strongly reddened by this attenuation.

To quantify this, we must integrate the attenuation of a bandpass $T(\lambda)$:

$$
Q(z_{\text{em}}) = \int e^{-\tau_{\text{eff}}} T(\lambda) \, d\lambda,
$$

the change in magnitude is then $\Delta m = -1.086 \ln Q(z)$. 
Madau et al. 1996

Diagram (a) shows transmission as a function of wavelength (Å) with multiple curves indicating different transmission levels. Diagram (b) displays magnitude (mag) as a function of redshift (z_em) with specific labels for ΔU_{300}, ΔB_{450}, ΔV_{606}, and ΔI_{814}. These curves illustrate the variation in magnitude across different redshift values.
Lyman Break
Galaxy
Selection

Put together K-corrections and HI opacity to identify colors of distant galaxies:

Steidel et al. 1995
Lyman Break Galaxy Selection

Model galaxy at z=3.0

relative flux

redshifted Lyman limit

unattenuated spectrum

attenuated spectrum

HST Filters

U_{300} B_{450} V_{806} I_{814}

observed wavelength (Å)

transmission


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Lyman Break Galaxy Selection

Steidel et al. (1999), seminal paper on the subject
Lyman Break Galaxy Selection

Steidel et al. (1999), seminal paper on the subject
Lyman Break Galaxy Selection

Steidel et al. 1999

Wavelength (Å)
Lyman Break Galaxy Selection

Composite Spectrum of nearly 1000 LBGs, Shapley et al. (2003)
Lyman Break Galaxy Selection

46 Galaxies, $<z>=4.13\pm0.26$

564 Galaxies, $<z>=3.04\pm0.24$

Steidel et al. 1999
### Lyman Break Galaxy Selection

Steidel et al. 1999

**Table 3**

<table>
<thead>
<tr>
<th>AB Magnitude Range</th>
<th>$\Sigma(z = 3)^c$</th>
<th>$V_{\text{eff}}(1, 0)^d$</th>
<th>$V_{\text{eff}}(0.2, 0)^d$</th>
<th>$V_{\text{eff}}(0.3, 0.7)^d$</th>
</tr>
</thead>
<tbody>
<tr>
<td>22.5–23.0</td>
<td>$0.002 \pm 0.001$</td>
<td>120</td>
<td>448</td>
<td>471</td>
</tr>
<tr>
<td>23.0–23.5</td>
<td>$0.021 \pm 0.004$</td>
<td>120</td>
<td>448</td>
<td>471</td>
</tr>
<tr>
<td>23.5–24.0</td>
<td>$0.087 \pm 0.011$</td>
<td>117</td>
<td>437</td>
<td>459</td>
</tr>
<tr>
<td>24.0–24.5</td>
<td>$0.194 \pm 0.016$</td>
<td>112</td>
<td>418</td>
<td>440</td>
</tr>
<tr>
<td>24.5–25.0</td>
<td>$0.380 \pm 0.023$</td>
<td>97</td>
<td>362</td>
<td>381</td>
</tr>
<tr>
<td>25.0–25.5</td>
<td>$0.495 \pm 0.049$</td>
<td>67</td>
<td>250</td>
<td>263</td>
</tr>
</tbody>
</table>

*Observed surface density.

* $R$ magnitudes.

* Objects per square arcminute in 0.5 mag interval for $z \sim 3$ sample. Each bin has been corrected for contamination by interlopers based on the spectroscopic sample. The errors reflect both Poisson counting and field-to-field variations.

* Effective survey volume per square arcminute for galaxies in each range of apparent magnitude, in units of $h^{-3}$ Mpc$^3$. The numbers in parentheses indicate the assumed cosmology, with $(\Omega_m, \Omega_{\Lambda})$.

\[ V_{\text{eff}}(m) \equiv \int dz p(m, z) dV/dz \]

$p(m,z)$ = probability that a galaxy with redshift $z$ and magnitude $m$ enters survey
Lyman Break Galaxy Selection

Steidel et al. 1999

Expected survey volumes for LBGs in HST HDF filters.
Lyman Break Galaxy Selection

Steidel et al. 1999

\[
\begin{align*}
\text{Z} \sim 3 \\
\alpha &= -1.60 \pm 0.13 \\
m_* &= 24.48 \pm 0.15 \\
\Phi_* &= 1.6 \times 10^{-2}
\end{align*}
\]

\[
\begin{align*}
\text{Z} \sim 4 \\
\alpha &= -1.60 \\
m_* &= 24.97 \\
\Phi_* &= 1.3 \times 10^{-2}
\end{align*}
\]
Lyman Break Galaxy Selection

Steidel et al. 1999

No Extinction

Extinction Corrected
Lyman Break Galaxy Selection

Dickinson, Papovich, Ferguson, & Budavari 2003
Lyman Break Galaxy Selection

Dickinson, Papovich, Ferguson, & Budavari 2003
Lyman Break Galaxy Selection

Dickinson, Papovich, Ferguson, & Budavari 2003
Lyman Break Galaxy Selection

Studies of Metallicities in LBGs

Pettini et al. 2002
Lyman Break Galaxy Selection

Studies of Metallicities in LBGs

Pettini et al. 2002

Pettini et al. 2002
Lyman Break Galaxy Selection

Studies of Metallicities in LBGs

Erb et al. 2006
Lyman Break Galaxy Selection

LBG selection works at higher redshift, Bouwens et al. 2007

“B”-dropouts (z~4) \[ (B_{435} - V_{606} > 1.1) \land [B_{435} - V_{606} > (V_{606} - z_{850}) + 1.1] \land (V_{606} - z_{850} < 1.6) \]

“V”-dropouts (z~5) \[ \left\{ [V_{606} - i_{775} > 0.9(i_{775} - z_{850})] \lor (V_{606} - i_{775} > 2) \right\} \land (V_{606} - i_{775} > 1.2) \land (i_{775} - z_{850} < 1.3) \]

“i”-dropouts (z~6) \[ (i_{775} - z_{850} > 1.3) \land \left\{ (V_{606} - i_{775} > 2.8) \lor [S/N(V_{606}) < 2] \right\} \]

\( \land \) is the logical *AND*, and \( \lor \) is the logical *OR*
Lyman Break Galaxy Selection

LBG selection works at higher redshift, Bouwens et al. 2007

“B”-dropouts (z~4)
Lyman Break Galaxy Selection

LBG selection works at higher redshift, Bouwens et al. 2007

“V”-dropouts (z~5)
Lyman Break Galaxy Selection

LBG selection works at higher redshift, Bouwens et al. 2007
Evolution of the UV LF from LBGs

Bouwens et al. 2007
Evolution of the UV LF from LBGs

Bouwens et al. 2007