Quantifying the Bimodal Color-Magnitude Distribution of Galaxies

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Background

• Wanted to characterize color and magnitude of nearby extragalactic neighborhood
  • u-r color (355 – 616 nm)
  • $M_r$ (Petrosian)

• Sloan Digital Sky Survey

• Low redshift galaxy sample (with reliable $z_{\text{spec}}$)
  • $0.004 < z < 0.08$
  • $-23.5 < M_r < -15.5$

• Acquired sample of 66,846 galaxies
Motivation

- Useful photometric distance indicator
- Two generally recognized populations of galaxies
  - Early types: E+So, redder
  - Late types: Sa-Sd, spirals and irregulars, bluer
- Apparently fundamentally distinct populations (IE not continuous in properties such as color)
  - Suggests physical differences
  - Formation differences
Observations
Incompleteness Correction

- Dimmer sources can’t be observed out to $z \sim 0.08$
- Some galaxies not observed due to fiber collisions
Aims

- “To quantitatively determine the variation in the mean and dispersion of the spectral colors of [the blue and red] distribution, as a function of luminosity
- To determine separate luminosity functions
- To relate the above to physical explanations
- To determine a best-fit cut in color versus absolute magnitude space to divide galaxies by type”
Parameterization

\[ \Phi = \Phi_r + \Phi_b \]

\[ \Phi(M_r, C_{ur}) = \phi(M_r)G \]

\[ G(C_{ur}, \mu, \sigma) = \frac{1}{\sigma\sqrt{2\pi}} \exp \left[ -\frac{(C_{ur} - \mu)^2}{2\sigma^2} \right] \]

- Fit Gaussians in 0.5 magnitude bins
Fitting

- Mean and standard deviation constrained to be continuous
- Fitted with a straight line and tanh function:
  \[ T(M_r) = p_0 + p_1 (M_r + 20) + q_0 \tanh \left( \frac{M_r - q_1}{q_2} \right) \]
- Crosses ~ red population
- Squares ~ blue population
- Iterated procedure
Red Pop (crosses)

- $\sigma$ shares transition magnitudes w/ $\mu$
- As magnitudes increase (dim), $\mu$ shifts blueward and $\sigma$ increases
- Consistent with increasing fraction of luminosity due to new star formation (colors of young stars more dependent on ages than old stars)
Blue Pop (Squares)

- At increasing (dimming) mags we see a gentle slope blueward.
  - Explained by metallicity-luminosity correlation
- Transition region too steep to be explained by metallicity
  - Increased dust
  - Decreased recent star formation
Parameterization

\[
\Phi = \Phi_r + \Phi_b
\]

\[
\Phi(M_r,C_{ur}) = \phi(M_r)G
\]

\[
G(C_{ur},\mu,\sigma) = \frac{1}{\sigma \sqrt{2\pi}} \exp \left[ -\frac{(C_{ur} - \mu)^2}{2\sigma^2} \right]
\]

- Fit Gaussians in 0.5 magnitude bins
Luminosity Function

$$\Phi(M_r, C_{ur}) = \phi(M_r)G$$

- Amplitudes fit with Schechter functions

$$\phi(M_r) = c\phi^* e^{-c(\alpha+1)(M_r-M^*)} e^{-c(M_r-M^*)}$$

- Blue distribution fit with double Schechter function

- 42% of r band lum. is in red distribution

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A single Schechter function was found to give a good fit to the red distribution ($\phi_r$) but not to the blue distribution ($\phi_b$). In the latter case, a significantly better fit was obtained by summing two Schechter functions (with a single value for $M^*$). Both the double- and single-Schechter function parameters are shown for $\phi_b$

The luminosity density in absolute magnitudes per Mpc$^3$. The percentage in brackets is the fraction relative to the total r-band luminosity density.
Galaxy Stellar Mass Function

\[ \log(Mass / L_r) = a + bC_{ur} \]

- 54-60% of stellar mass density is in red distribution
Dividing the Sample

- Often useful to study population of one type or another
- Need a good indicator to split population

Blue and Red population distribution model with optimal indicator shown as grey dash dotted line
A word on completeness and reliability

- Completeness: fraction of population selected in sample
- Reliability: fraction of sample correctly selected

Optimal indicator: maximize $C_r R_r C_b R_b$

$$C'_{wr}(M_r) = 2.06 - 0.244 \tanh \left( \frac{M_r + 20.07}{1.09} \right)$$

- Not perfect (esp. at bright magnitudes)
  - Suggest using color magnitude information in concert with morphology and spectroscopy when available
Conclusions

- Quantitatively determined the variation in the mean and dispersion of the spectral colors of each distribution, as a function of luminosity
- Determined separate luminosity functions
- Related the above to physical explanations
- Determined a best-fit cut in color versus absolute magnitude space to divide galaxies by type
Appendix

Parameterization
\[ \Phi = \Phi_r + \Phi_b \]
\[ \Phi(M_r, C_{ur}) = \phi(M_r)G \]
\[ G(C_{ur}, \mu, \sigma) = \frac{1}{\sigma \sqrt{2\pi}} \exp \left[ -\frac{(C_{ur} - \mu)^2}{2\sigma^2} \right] \]

Parameterization
\[ \phi(M_r) = c \phi^* e^{-c(\alpha + 1)(M_r - M^*)} e^{-e^{-c(M_r - M^*)}} \]

<table>
<thead>
<tr>
<th>Distribution</th>
<th>( M^* - 5 \log h_0 )</th>
<th>( \phi^* h_0^{-2} )</th>
<th>( \alpha )</th>
<th>( \phi^* h_0^{-2} )</th>
<th>( \alpha' )</th>
<th>( j + 2.5 \log h_0^3 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \phi_r )</td>
<td>-21.49 ± 0.03</td>
<td>2.25 ± 0.08</td>
<td>-0.83 ± 0.02</td>
<td>...</td>
<td>...</td>
<td>-14.79 (42%)</td>
</tr>
<tr>
<td>( \phi_b )</td>
<td>-20.60 ± 0.08</td>
<td>2.02 ± 0.21</td>
<td>2.35 ± 0.37</td>
<td>-1.35 ± 0.05</td>
<td>-15.13 (58%)</td>
<td></td>
</tr>
<tr>
<td>( \phi_c )</td>
<td>-21.29 ± 0.03</td>
<td>2.89 ± 0.13</td>
<td>-1.18 ± 0.02</td>
<td>...</td>
<td>...</td>
<td>-15.08</td>
</tr>
</tbody>
</table>

- A single Schechter function was found to give a good fit to the red distribution (\( \phi_r \)) but not to the blue distribution (\( \phi_b \)). In the latter case, a significantly better fit was obtained by summing two Schechter functions (with a single value for \( M^* \)). Both the double- and single-Schechter function parameters are shown for \( \phi_b \).
- The luminosity density in absolute magnitudes per Mpc\(^3\). The percentage in brackets is the fraction relative to the total r-band luminosity density.

Gaussian \( \mu \) and \( \sigma \) Tanh fits and optimal color cut
\[ T(M_r) = p_0 + p_1(M_r + 20) + q_0 \tanh \left( \frac{M_r - q_1}{q_2} \right) \]

Parameterization
\[ T(M_r) = p_0 + p_1(M_r + 20) + q_0 \tanh \left( \frac{M_r - q_1}{q_2} \right) \]

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<thead>
<tr>
<th>Distribution</th>
<th>( p_0 )</th>
<th>( p_1 )</th>
<th>( q_0 )</th>
<th>( q_1 )</th>
<th>( q_2 )</th>
<th>( (q_1/M_r)^b )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( p_r )</td>
<td>2.279 ± 0.006</td>
<td>-0.037 ± 0.006</td>
<td>-0.108 ± 0.017</td>
<td>-19.81 ± 0.07</td>
<td>0.96 ± 0.16</td>
<td>1.8 \times 10^{10}</td>
</tr>
<tr>
<td>( \sigma_r )</td>
<td>0.152 ± 0.006</td>
<td>0.008 ± 0.006</td>
<td>0.044 ± 0.018</td>
<td>-19.91 ± 0.18</td>
<td>0.94 ± 0.40</td>
<td>2.0 \times 10^{10}</td>
</tr>
<tr>
<td>( p_b )</td>
<td>1.790 ± 0.014</td>
<td>-0.053 ± 0.008</td>
<td>-0.363 ± 0.029</td>
<td>-20.75 ± 0.05</td>
<td>1.12 ± 0.10</td>
<td>2.6 \times 10^{10}</td>
</tr>
<tr>
<td>( \sigma_b )</td>
<td>0.298 ± 0.004</td>
<td>0.014 ± 0.007</td>
<td>-0.067 ± 0.014</td>
<td>-19.90 ± 0.07</td>
<td>0.58 ± 0.19</td>
<td>0.9 \times 10^{10}</td>
</tr>
</tbody>
</table>

- The results of fitting a straight line plus a tanh function (eq. [9]) to the variations, in the means (\( \mu \)) and dispersions (\( \sigma \)), of the red and blue distributions as a function of \( M_r \) (eqs. [7] and [8]). The \( p \) parameters represent the straight line, while the \( q \) parameters represent the tanh function. The fitted lines are shown in Figs. 5 and 6. Note that the errors quoted do not include systematic uncertainties due to photometric calibration or \( k \)-corrections.
- The transition midpoint approximately converted to stellar mass (see § 5.4).

<table>
<thead>
<tr>
<th>Distribution</th>
<th>( C'_{ur} (M_r) = 2.06 - 0.244 \tanh \left( \frac{M_r + 20.07}{1.09} \right) )</th>
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