PROBLEM SET # 3

Astro 512 – Spring 2017
Extragalactic Astronomy

In this problem set, you will use a standard package for stellar population synthesis, described at the end of this problem set, "Flexible Population Synthesis" or FSPS. The code is developed by Charlie Conroy and maintained in a GitHub repository at `https://github.com/cconroy20/fsps`. There is a python wrapper, `python-FSPS`, with clear installation instructions `http://dan.iel.fm/python-fsps/`[1].

In all that follows, assume that star formation started 12.5 Gyrs ago. You will neglect dust and metallicity evolution for simplicity.

Problem 1: Age and Metallicty Spreads on the Red and Blue Sequences

As shown in Baldry et al (2004) for galaxies in SDSS, galaxies separate into two sequences on a plot of magnitude versus color: a red one that is biased towards luminous galaxies, and a blue one that is biased towards fainter galaxies. The distribution and fits to the mean $u-r$ color as a function of magnitude are shown in the attatched figures, along with a formula describing the fitting function used in the figures.

a) Generate a grid of models for $\tau = 0, 2, 4, 8, \infty$, assuming a standard exponentially declining SFH (a "τ-model") and a total stellar mass of 5×10^{10} M$_\odot$. Do this first for a single metallicity (e.g., solar) then modify your code to compute spectra for a series of metallicities ($\log_1 0Z/Z_\odot = -1.5$, -1, -0.5, -0.2, 0, $+0.2$) (which will be very slow).

b) Derive the mean stellar age at the present day for a given value of τ, and then calculate the mean stellar ages for your specific grid of models. For example, a value of $\tau = 0$ (instantaneous burst 12.5 Gyrs ago) would have a mean stellar age of 12.5 Gyrs, and a constant star formation rate starting 12.5 Gyrs ago would have a mean stellar age of 6.25 Gyrs.

Make a scatter plot of $u-r$ vs weighted age, color-coded by metallicity, with a legend. Shade the region of color occupied by red sequence galaxies brighter than $M_r = -18$, and by blue sequence galaxies fainter than $M_r = -21$. Use this plot to identify the broad ranges of age and metallicity that might be consistent with red- and blue-sequence galaxies (in the absence of dust and/or complicated star formation histories), as follows.

c) If all galaxies had solar metallicity, what spread in mean stellar age would be required to explain the range in colors (1) on the red sequence from $-24 < M_r < -22$, (2) on the red sequence from $-20 < M_r < -18$, (3) on the blue sequence from $-23 < M_r < -21$ (where there are actually very few galaxies) and (4) on the blue sequence from from $-19 < M_r < -16$?

[1]the MESA Isochrones and Stellar Tracks (MIST) models are the default isochrone set used in FSPS. The MIST models can be much slower when computing composite stellar populations due to their finer age and mass sampling. To instead use the Padova isochrones, edit `SPS_HOME/src/sps_vars.f90` and be sure to `make clean` and `make`; then go back to your `python-FSPS` directory and `python setup.py install` for a fresh compile

d) Would it be possible to achieve the change in mean color along the red-sequences with metallicity alone (i.e., all galaxies have the same mean age, and only metallicity drives the change in color)? Why or why not? What about the blue-sequence?

Problem 2: The movement of galaxies from one sequence to the other — Red to Blue

You will now constrain how galaxies might move from one sequence to another. They can do so by either reactivating star formation in a red galaxy, or by truncating star formation in a blue galaxy.

Based on your results in (1), adopt a smooth τ-model star formation history that can produce appropriate colors for a galaxy on the red sequence at $M_r = -20$ today, at solar metallicity.

a) FSPS records both the "mass formed" and the stellar mass present today. What is the total mass in stars formed to generate the galaxy with $M_r = -20$ today? And what is the stellar mass of the galaxy at the present day? Note that these are not the same quantities because some fraction of stars will have evolved and exploded. What fraction of the original stellar mass was lost to stellar evolution? Be aware that in some models, there is the option of incorporating "recycling" that turns this recycled gas back into stars.

b) On a plot analogous to Figure 6 of Baldry et al (2004), with the bimodal sequences overplotted, add a locus showing how the galaxy changes in both color and magnitude during its evolution to its current location on the red sequence. Mark the locus with points separated by a fixed time interval, and provide a legend for interpreting the time points.

c) Based on your plot, how long would it take until this galaxy first moved into the "red sequence" (i.e., within 1σ of the peak of the locus)? Using your plot of lookback time vs redshift from one of the first problem sets, at roughly what redshift would this occur?

Now assume that this somewhat quiescent galaxy is brought back to life by the infall of fresh gas, which produces a burst of star formation. Assume the burst forms another $\sim$5% of the galaxy's initial mass.

d) On your plot from (b), add a locus showing how the galaxy changes in both color and magnitude during the burst and the subsequent fading back to the red sequence. Mark the locus with points separated by a fixed time interval (either linear, or logarithmically spaced, depending on which seems more informative), including a legend.

e) During the burst, does the galaxy make it to the blue sequence? After how many years does the galaxy come back to within 1σ of the red sequence?

f) By how much do the above times shorten if the burst were only 1% of the galaxy's stellar mass?

Problem 3: The movement of galaxies from one sequence to the other — Blue to Red

Now consider the truncation of star formation in a blue sequence galaxy. Generate a smooth τ-model star formation history that can produce appropriate colors for a galaxy on the blue sequence at $M_r = -20$, assuming solar metallicity.

a) What value of τ did you adopt?

b) What is the initial stellar mass of this model, and how does it compare to the initial stellar mass of the red sequence galaxy at the same magnitude?

For the exponentially declining SFH adopted above, truncate the star formation.

c) On a plot analogous to Figure 6 of Baldry et al (2004), with the bimodal sequences overplotted, add a locus showing how the galaxy changes both color and magnitude after truncation and fades to the red sequence. Mark the locus with points separated by a fixed time interval (linear or logarithmic).

d) How many years does it take the galaxy redden to within 1σ of the red sequence?

e) How long can the galaxy spend in the "green valley" between the sequences?

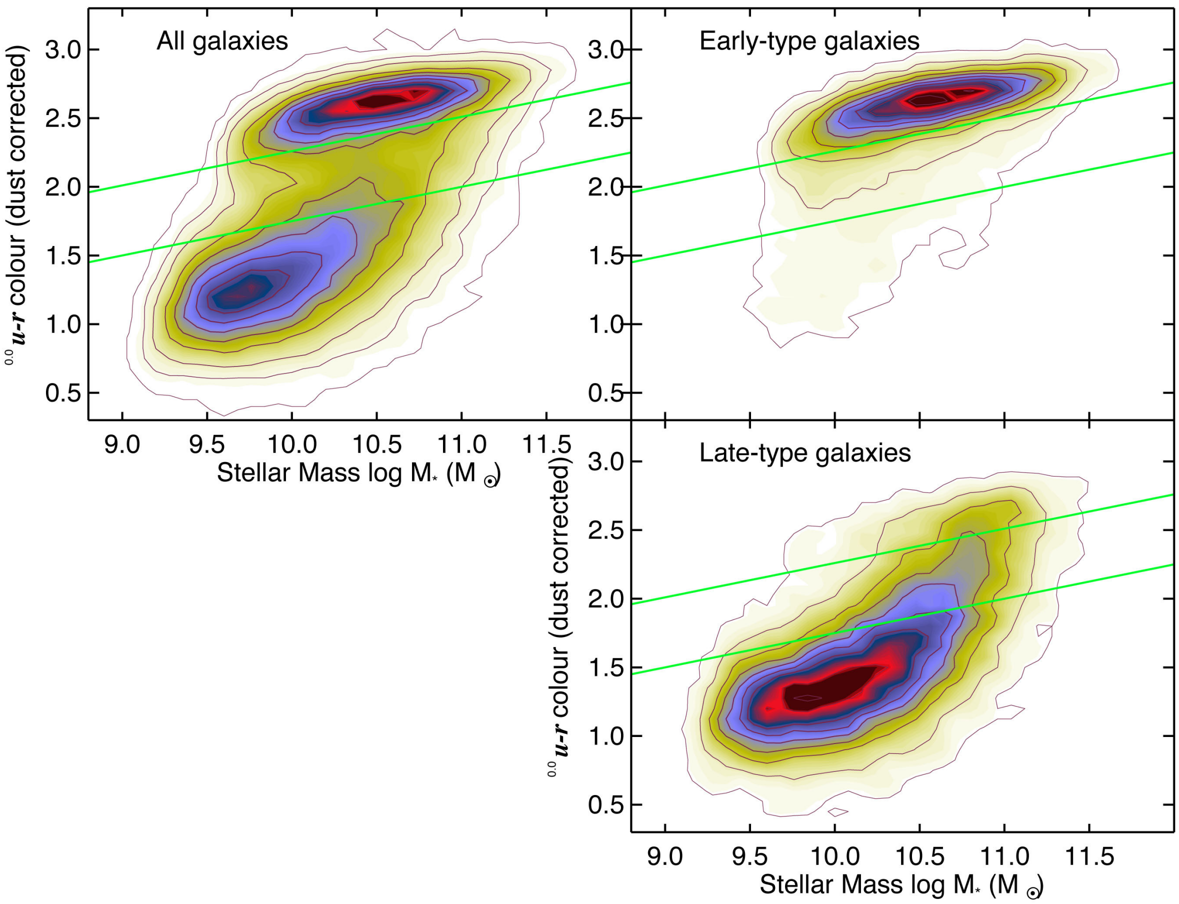
f) Would the duration of the above times shorten or lengthen if you had started with a constant star formation rate (i.e. larger τ)? Explain your answer briefly.

Problem 4: Bimodality as a morphological effect

It is also possible that bimodality does *not* reflect an evolutionary sequence, but instead is just a reflection of variations in the bulge fraction (see the plot below, using results from GalaxyZoo, by Schawinski et al 2014).

To approximate this behavior, co-add your "ancient burst" and "constant SFR" models in different proportions, maintaining the same stellar mass at the present day, but changing the bulge fraction f_{bulge} smoothly from zero to one. (Note: If your constant SFR models are too blue, you may want to substitute a slightly less extreme disk model with a "large but not infinite" value of τ.)

a) Plot how the $u - r$ color changes as a function of f_{bulge}. Over what ranges in bulge fraction will the galaxy appear to be on the blue sequence, on the red sequence, or in the green valley (assuming $M_r = -20$)? How challenging is it to have a galaxy appear in the green valley?



Color-Magnitude Data from Baldry et al (2004)

The plot below is an update on the fits in Baldry et al (2004), using methods that were improved in Baldry et al 2006. The plot is made using a gaussian decomposition of the color distributions at each magnitudes. Data and fits for the plots can be found at:

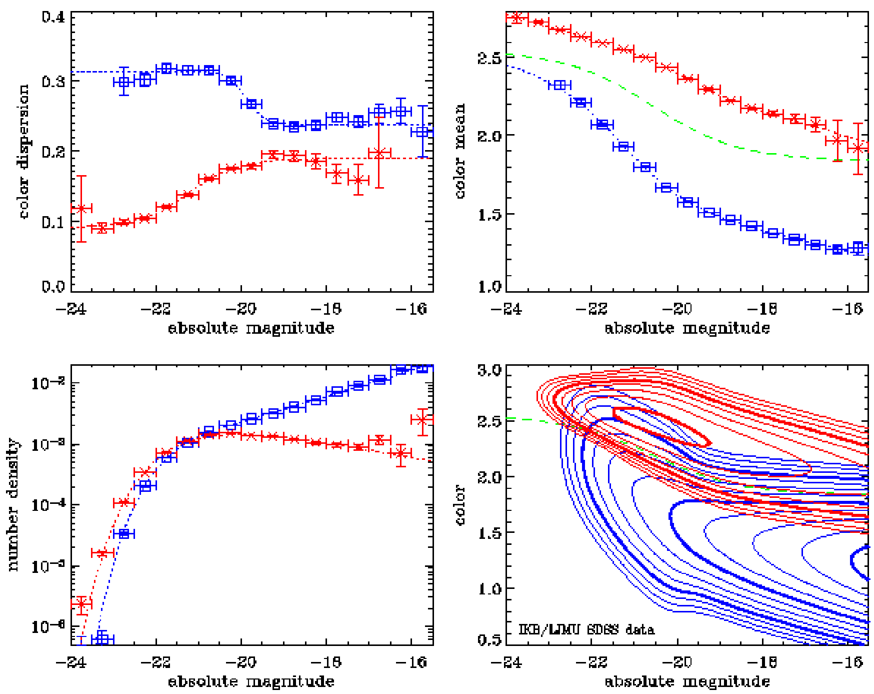
`http://www.astro.ljmu.ac.uk/~ikb/research/data/dg-fits-usingconc.txt`

and

`http://www.astro.ljmu.ac.uk/~ikb/research/data/tanh-sch-paras.txt`

which I took from:

`http://www.astro.ljmu.ac.uk/~ikb/research/bimodality-paperI.html`



The values of the parameters in the fits above use the fitting equation:

Both μ and σ are constrained to be contiguous functions of M_r, in particular, a straight line plus a tanh function given by

$$\mathcal{T}(M_r) = p_0 + p_1(M_r + 20) + q_0 \tanh\left[\frac{M_r - q_1}{q_2}\right] \quad (9)$$

Using the FSPS and python-FSPS codes

For this problem set, you will be using the package Flexible Stellar Population Synthesis (FSPS), written in Fortran, and the python wrapper, `python-FSPS`. You should first install FSPS and then `python-FSPS`. The installation instructions found in the GitHub repository are fairly straightforward for both. For FSPS, make sure to add the `SPS_HOME` environment variable in your `.cshrc` or `.bashrc` profile. For installation on the department linux machines, edit the `Makefile` to include additional compilation flags: `F90FLAGS = -O3 -march=native -cpp -fPIC`.

You can change the isochrone set and spectral library used (among other things) in `sps_vars.f90` before you run `make`. Any time you re-compile FSPS you will need to re-run the setup script for `python-FSPS`.

Everything you do in FSPS revolves around the `StellarPopulation` object, which allows you to generate complex stellar populations, with almost every input parameter designed to be as flexible as possible: IMF, SFH, metallicity, dust prescription, etc.

```python
import fsps
sp = fsps.StellarPopulation(zcontinuous=1) # allows for arbitrary metallicities
sp.libraries # Check isochrone set and spectral library
```

For this problem set, you will be using the `sfh=1` option, which is a 6-parameter τ-model (an exponentially declining SFH with the possibility of adding an additional constant or burst component). All of this is included in the documentation for FSPS, and is on the `python-FSPS` website (which also has useful examples for generating SEDs for your stellar populations).

```python
sp.params['sfh'] = 1 # use sfh=0 for bursts
sp.params['const'] = 0.0 # fraction of mass formed in constant component
sp.params['fburst'] = 0.0 # fraction of mass formed in burst component
sp.params['tburst'] = 0.0 # age of the burst
sp.params['tau'] = 2.0 # half-life of tau-model in Gyr [0.1-10]
sp.params['logzsol'] = 0.0 # log Z/Zsun if using zcontinuous
sp.params['sf_start'] = 1.6 # SF starts universe is 1.6 Gyrs
```

To return the u,g,r,i,z magnitudes of your stellar population as observed today, you will use the `get_mags` function, which returns a 5-element list corresponding to the u,g,r,i,z magnitudes.

```python
sdss_bands = fsps.find_filter('sdss')
mag_array = sp.get_mags(tage=14.1, bands=sdss_bands) # tage in Gyrs
```

The output has been normalized to have formed $1 M_{\odot}$ in the specified `tage`. If you do not request a specific `tage`, the function will return a 94 by 5 element array, corresponding to the u,g,r,i,z magnitudes at each of the 94 ages in the Padova isochrones (for MIST, there are 107 ages). IMPORTANT: each of these ages has been normalized to $1 M_{\odot}$, so you will need to normalize carefully!

Other useful attributes of the `StellarPopulation` object:

```
sp.formed_mass # total mass formed (Msun), the integral of the SFH
sp.stellar_mass # surviving stellar mass (Msun)
sp.ssp_ages # log[ time (years) ] of each SSP
sp.sfr # Star formation rate in Msun / year
```