Group_Meeting_032118

March 21, 2018

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```
In [1]: import numpy as np, matplotlib.pyplot as plt, matplotlib as mpl, seaborn as sns
        import pandas as pd
        import pcmdpy as ppy
        %matplotlib inline
```

```
GPU acceleration not available, sorry
No module named 'pycuda'
```

```
In [2]: sns.set_context('poster')
```

```
In [3]: try:
            ppy.gpu_utils.initialize_gpu(n=0)
            GPU_AVAIL = True
        except:
            GPU_AVAIL = False
```

```
Can't initialize GPU, _GPU_AVAIL is set to False
```

```
In [4]: f = ppy.instrument.m31_filters()
        iso_model = ppy.isochrones.Isochrone_Model(f)
        driv = ppy.driver.Driver(iso_model, gpu=GPU_AVAIL)
```

```
In [28]: def plot_pcmd(pcmd, bins=100, norm=mpl.colors.LogNorm(), ax=None, title=None, isochrone
             if ax is None:
                 fig, ax = plt.subplots(figsize=(10, 6))
             g = ppy.galaxy.DefaultSSP.get_model(np.array([0., -2., 2., 10.]))
             ax.hist2d(pcmd[1], pcmd[0], bins=bins, norm=norm, normed=True)
             iso_model.plot_isochrone(g, axes=ax, zorder=-1, **isochrone_kwargs)
             if title is not None:
                 ax.set_title(title)
             return ax
```

```
In [6]: def plot_model(model, N_im=256, **plot_kwargs):
            pcmd, _ = driv.simulate(model, N_im)
            return plot_pcmd(pcmd, **plot_kwargs)
```

1 Pixel-CMDs

Ben Cook
Conroy Group Meeting
21 March 2018

2 Background

Observing a galaxy (photometry, spectra maybe, etc.)
Our goal is generically to measure its:

- Stellar Mass
- Metal Abundances
- Star Formation History
- Dust Content
- ...

A galaxy's light is (primarily) contributed by the stars it contains.
So, we combine our knowledge of stars and their evolution into understanding galaxies.
** Stellar Population Synthesis **

2.1 Integrated Stellar Populations

or: SED Modelling
Leja et al. 2018

2.2 Integrated Stellar Populations

- Can assume fully-populated isochrones
- Typically need wide spectral coverage
- Uncertanties come from rare, highly-evolved phases of stellar evolution (+AGN, dust, ...)

2.3 Resolved Stellar Populations

or: CMD modelling ** M13 (as seen by HST)**

2.4 Resolved Stellar Populations

2.5 Resolved Stellar Populations

- Observe individual stars, and compare to isochrone models
- Often only need 2 colors to measure metallicity, SFH
- Limited by spatial resolution (crowding) and exposure (faintness limit)

2.6 Semi-Resolved Stellar Populations

or: Pixel-CMDs

We're studying the intermediate regime, where: * Can't resolve individual stars (crowding limited) * Can't assume isochrones are fully populated (surface-brightness fluctuations)

It makes sense to describe systems by N_{pix}: the typical number of stars per pixel

- Resolved CMDs: $N_{pix} \ll 1$
- Semi-Resolved Stellar Populations: $N_{pix} \sim 1 \rightarrow 10^7$
- Integrated Stellar Populations: $N_{pix} \gg 10^7$

Due to Poisson fluctuations, some pixels will have fewer bright-rare stars than others.

- Surface-brightness fluctuations contain information!

M31 Bulge (PHAT survey)

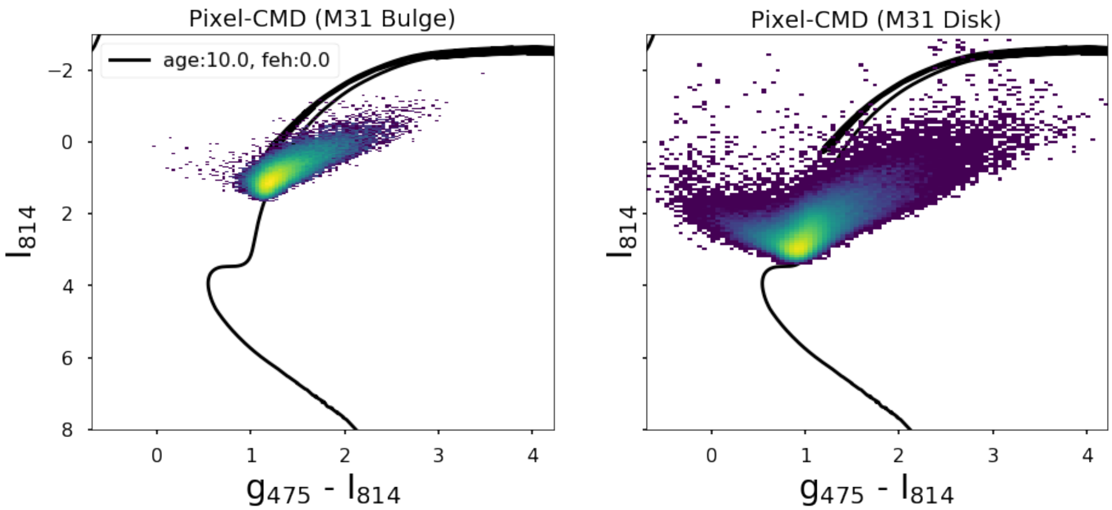
What is the distribution of colors and magnitudes on a pixel-by-pixel basis?

Pixel Color-Magnitude Diagrams

In [30]:
```
pcmd_m31_b = np.loadtxt('../../data/m31_bulge_M2.dat', unpack=True)[::-1]
pcmd_m31_d = np.loadtxt('../../data/m31_b06-263.dat', unpack=True)[::-1]
norm = mpl.colors.LogNorm()
```

In [31]:
```
fig, axes = plt.subplots(ncols=2, figsize=(15, 6), sharex=True, sharey=True)
_ = plot_pcmd(pcmd_m31_b, title='Pixel-CMD (M31 Bulge)', norm=norm, ax=axes[0], isochro
_ = plot_pcmd(pcmd_m31_d, title='Pixel-CMD (M31 Disk)', norm=norm, ax=axes[1], isochron
axes[0].set_ylim([8, -3.])
axes[0].legend(loc=0)
```

Out[31]:
```
<matplotlib.legend.Legend at 0x1098f0828>
```



3 The Basic Model

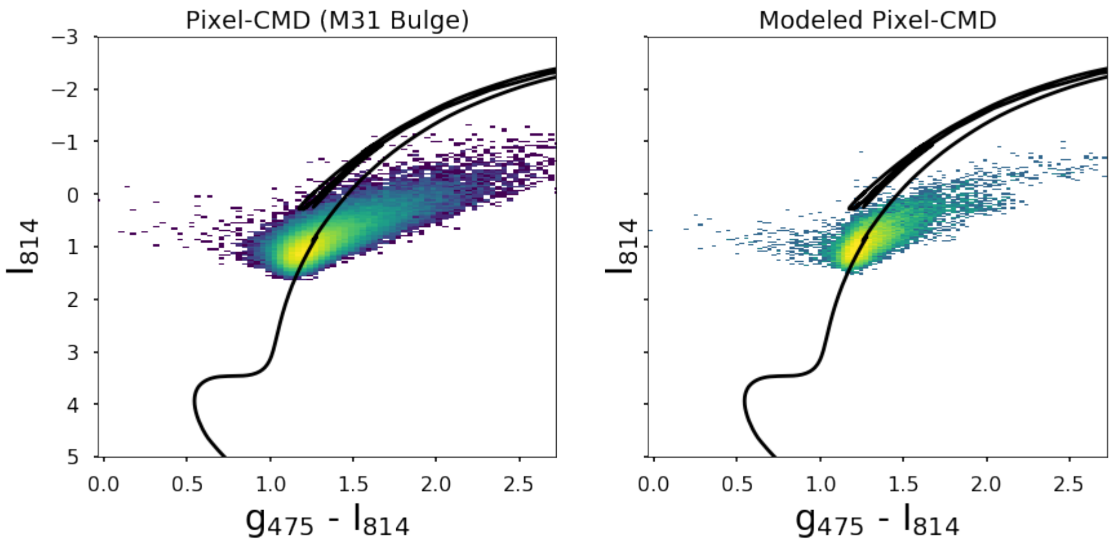
For a given population of stars (metallicity, Star-formation History, IMF), want to create a forward-model of the image and pixel-CMD

- use isochrones (magnitude, color, mass) from MIST
- assume each pixel in the image contains roughly N_{pix} stars
- randomly populate the pixels with stars from the isochrones
- apply observational effects (dust extinction, HST PSF, ...)
- compare resulting pixel-CMD to observed data

In [9]:
```
m31_model = ppy.galaxy.DefaultTau.get_model(np.array([0.2, -2., 2.3, 2.5]), iso_step=-1)
N_im = 128
if GPU_AVAIL:
    N_im = 1024
    m31_model = ppy.galaxy.DefaultTau.get_model(np.array([0.2, -2., 2.3, 2.5]))
pcmd_model_b, _ = driv.simulate(m31_model, N_im, system='ab')
```

In [32]:
```
fig, axes = plt.subplots(ncols=2, figsize=(14, 6), sharey=True, sharex=True)
plot_pcmd(pcmd_m31_b, title='Pixel-CMD (M31 Bulge)', ax=axes[0], isochrone_kwargs={'sys
plot_pcmd(pcmd_model_b, title='Modeled Pixel-CMD', ax=axes[1], isochrone_kwargs={'syste
axes[0].set_ylim([5., -3.]);
```

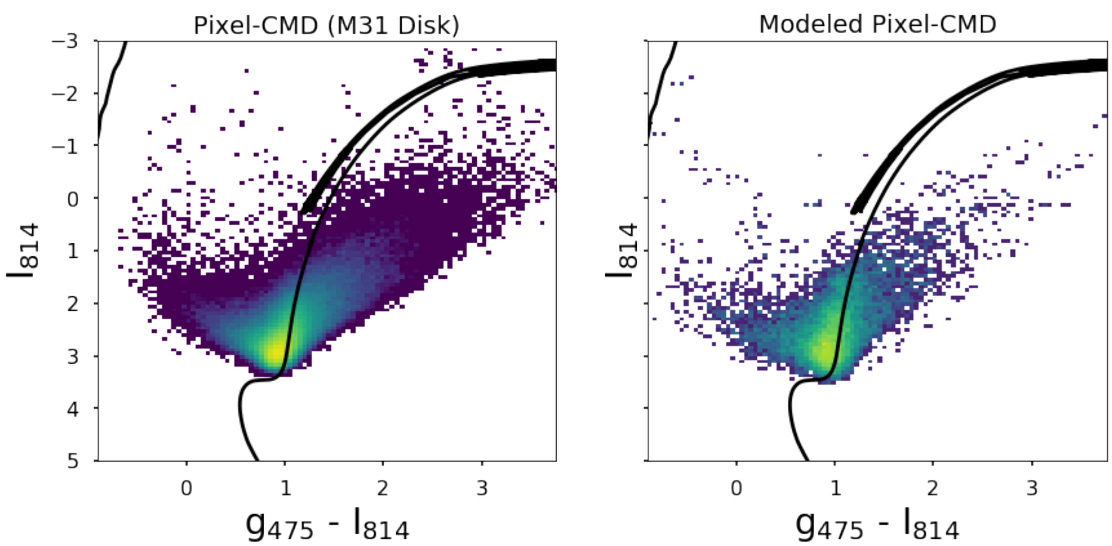
Out[32]: (5.0, -3.0)




```
In [10]: m31_d_model = ppy.galaxy.DefaultTau.get_model(np.array([-0.1, -2., 1.5, 5.]), iso_step=
         N_im = 128
         if GPU_AVAIL:
             N_im = 1024
             m31_d_model = ppy.galaxy.DefaultTau.get_model(np.array([-0.1, -2., 1.5, 5.]))
         pcmd_model_d, _ = driv.simulate(m31_d_model, N_im, system='ab')
```

```
In [36]: fig, axes = plt.subplots(ncols=2, figsize=(14, 6), sharey=True, sharex=True)
         plot_pcmd(pcmd_m31_d, title='Pixel-CMD (M31 Disk)', ax=axes[0], isochrone_kwargs={'syst
         plot_pcmd(pcmd_model_d, title='Modeled Pixel-CMD', ax=axes[1], isochrone_kwargs={'syste
         axes[0].set_ylim([5., -3.]);
```

```
Out[36]: (5.0, -3.0)
```



4 Model parameters

4.1 Npix: integrated stellar mass

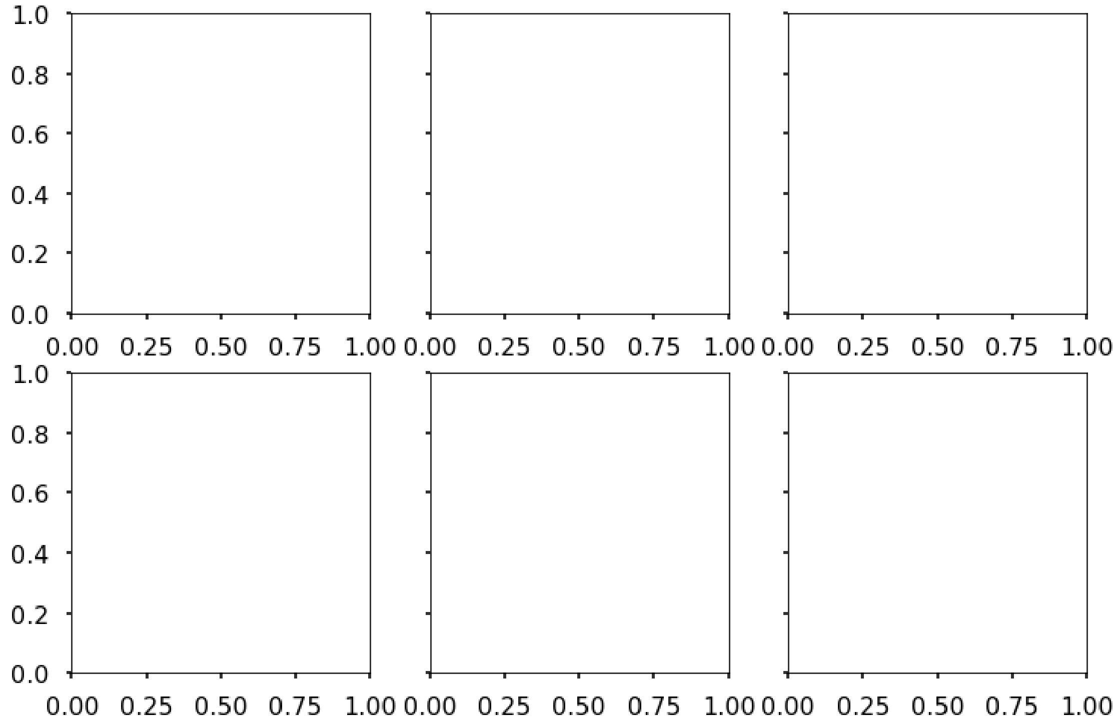
- increases magnitude
- narrows pCMD distribution

In [7]:
```
N_im = 128
if GPU_AVAIL:
    N_im = 1025
```

In [39]:
```
g1 = ppy.galaxy.DefaultSSP.get_model(np.array([0., -2., 2., 10.]))
g2 = ppy.galaxy.DefaultSSP.get_model(np.array([0., -2., 3., 10.]))
g3 = ppy.galaxy.DefaultSSP.get_model(np.array([0., -2., 4., 10.]))

pcmd1_n, im1_n = driv.simulate(g1, N_im)
pcmd2_n, im2_n = driv.simulate(g2, N_im)
pcmd3_n, im3_n = driv.simulate(g3, N_im)
```

In [21]:
```
fig, a = plt.subplots(ncols=3, nrows=2, figsize=(10, 6), sharex='row', sharey='row')
a[0,0].imshow(im1_n[0],cmap='Greys_r'),a[0,0].set_title(r'$N_{pix}$=10$^2$')
a[0,1].imshow(im2_n[0],cmap='Greys_r'),a[0,1].set_title(r'$N_{pix}$=10$^3$')
a[0,2].imshow(im3_n[0],cmap='Greys_r'),a[0,2].set_title(r'$N_{pix}$=10$^4$')
plot_pcmd(pcmd1_n,ax=a[1,0]), plot_pcmd(pcmd2_n,ax=a[1,1]), plot_pcmd(pcmd3_n,ax=a[1,2]
a[1,0].set_ylim([5., -5.]),a[1,0].set_xlim([0.5, 3]),plt.tight_layout()
```

```
---------------------------------------------------------------------------

NameError                                 Traceback (most recent call last)

<ipython-input-21-bc941d9323a5> in <module>()
  1 fig, a = plt.subplots(ncols=3, nrows=2, figsize=(12, 8), sharex='row', sharey='row')
----> 2 a[0,0].imshow(im1_n[0],cmap='Greys_r'),a[0,0].set_title(r'$N_{pix}$=10$^2$')
  3 a[0,1].imshow(im2_n[0],cmap='Greys_r'),a[0,1].set_title(r'$N_{pix}$=10$^3$')
  4 a[0,2].imshow(im3_n[0],cmap='Greys_r'),a[0,2].set_title(r'$N_{pix}$=10$^4$')
  5 plot_pcmd(pcmd1_n,ax=a[1,0]), plot_pcmd(pcmd2_n,ax=a[1,1]), plot_pcmd(pcmd3_n,ax=a[1


NameError: name 'im1_n' is not defined
```



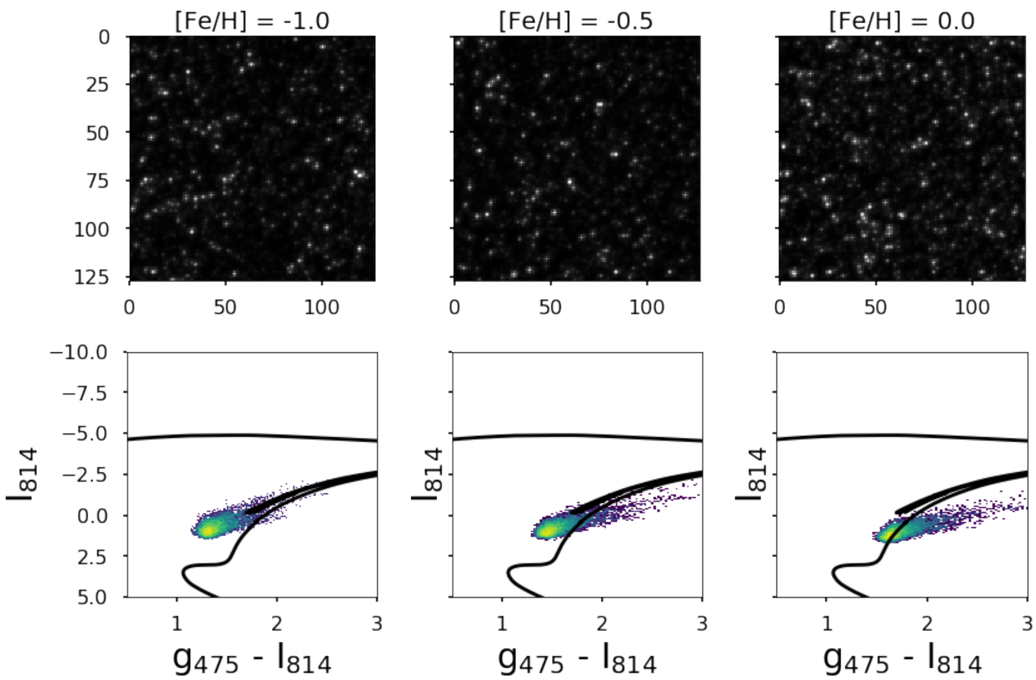
4.2 [Fe/H]: Metal Abundance

- Shifts pCMD towards red
- Also alters shape of pCMD distribution

In [37]:
```
g1 = ppy.galaxy.DefaultSSP.get_model(np.array([-1., -2., 2., 10.]))
g2 = ppy.galaxy.DefaultSSP.get_model(np.array([-0.5, -2., 2., 10.]))
g3 = ppy.galaxy.DefaultSSP.get_model(np.array([0., -2., 2., 10.]))

pcmd1_f, im1_f = driv.simulate(g1, N_im)
pcmd2_f, im2_f = driv.simulate(g2, N_im)
pcmd3_f, im3_f = driv.simulate(g3, N_im)
```

In [38]:
```
fig, a = plt.subplots(ncols=3, nrows=2, figsize=(10, 6), sharex='row', sharey='row')
a[0,0].imshow(im1_f[0],cmap='Greys_r'),a[0,0].set_title(r'[Fe/H] = -1.0')
a[0,1].imshow(im2_f[0],cmap='Greys_r'),a[0,1].set_title(r'[Fe/H] = -0.5')
a[0,2].imshow(im3_f[0],cmap='Greys_r'),a[0,2].set_title(r'[Fe/H] = 0.0')
plot_pcmd(pcmd1_f,ax=a[1,0]),plot_pcmd(pcmd2_f,ax=a[1,1]),plot_pcmd(pcmd3_f,ax=a[1,2])
a[1,0].set_ylim([5., -10.]),a[1,0].set_xlim([0.5, 3]),plt.tight_layout()
```

Out[38]:
```
((5.0, -10.0), (0.5, 3), None)
```



4.3 E(B-V): Dust Extinction

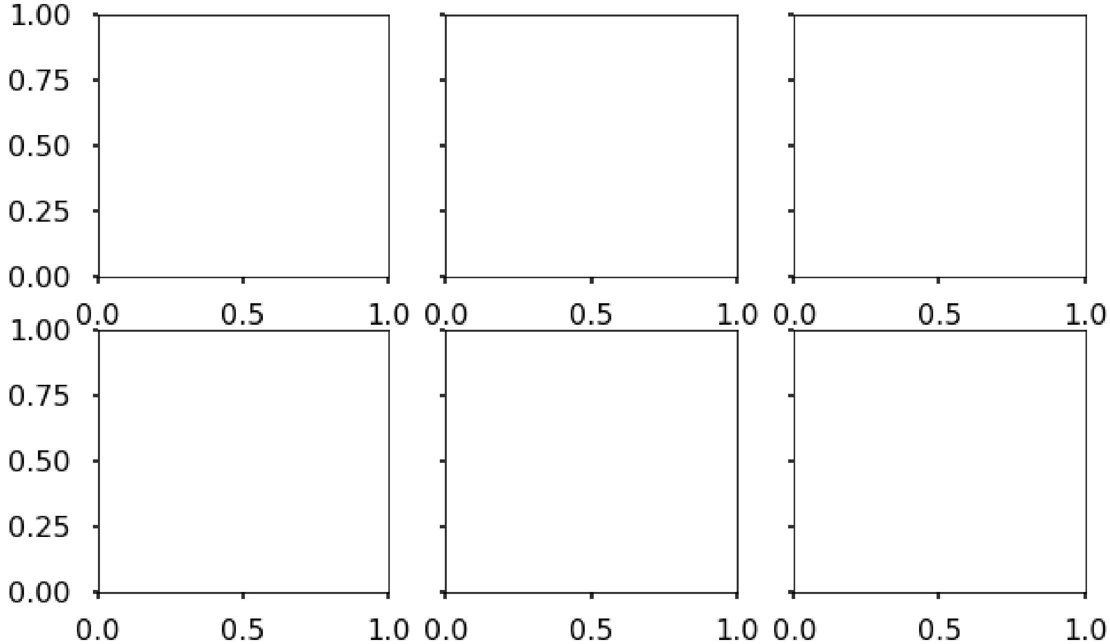
- Shifts pCMD towards red

In [41]:
```
g1 = ppy.galaxy.DefaultSSP.get_model(np.array([0., -1., 2., 10.]))
g2 = ppy.galaxy.DefaultSSP.get_model(np.array([0., -0.5, 2., 10.]))
g3 = ppy.galaxy.DefaultSSP.get_model(np.array([0., 0., 2., 10.]))

pcmd1_d, im1_d = driv.simulate(g1, N_im)
pcmd2_d, im2_d = driv.simulate(g2, N_im)
pcmd3_d, im3_d = driv.simulate(g3, N_im)
```

In [24]:
```
fig, a = plt.subplots(ncols=3, nrows=2, figsize=(10, 6), sharex='row', sharey='row')
a[0,0].imshow(im1_d[0], cmap='Greys_r'),a[0,0].set_title(r'E(B-V) = 0.1')
a[0,1].imshow(im2_d[0], cmap='Greys_r'),a[0,1].set_title(r'E(B-V) = 0.3')
a[0,2].imshow(im3_d[0], cmap='Greys_r'),a[0,2].set_title(r'E(B-V) = 1.0')
plot_pcmd(pcmd1_d, ax=a[1,0]), plot_pcmd(pcmd2_d, ax=a[1,1]), plot_pcmd(pcmd3_d, ax=a[1
a[1,0].set_ylim([5., -10.]),a[1,0].set_xlim([0.5, 5]),plt.tight_layout()
```

```
---------------------------------------------------------------------------

NameError                                 Traceback (most recent call last)

<ipython-input-24-7b444f7b5b7c> in <module>()
  1 fig, a = plt.subplots(ncols=3, nrows=2, figsize=(10, 6), sharex='row', sharey='row')
```

```
----> 2 a[0,0].imshow(im1_d[0], cmap='Greys_r'),a[0,0].set_title(r'E(B-V) = 0.1')
      3 a[0,1].imshow(im2_d[0], cmap='Greys_r'),a[0,1].set_title(r'E(B-V) = 0.3')
      4 a[0,2].imshow(im3_d[0], cmap='Greys_r'),a[0,2].set_title(r'E(B-V) = 1.0')
      5 plot_pcmd(pcmd1_d, ax=a[1,0]), plot_pcmd(pcmd2_d, ax=a[1,1]), plot_pcmd(pcmd3_d, ax=


    NameError: name 'im1_d' is not defined
```

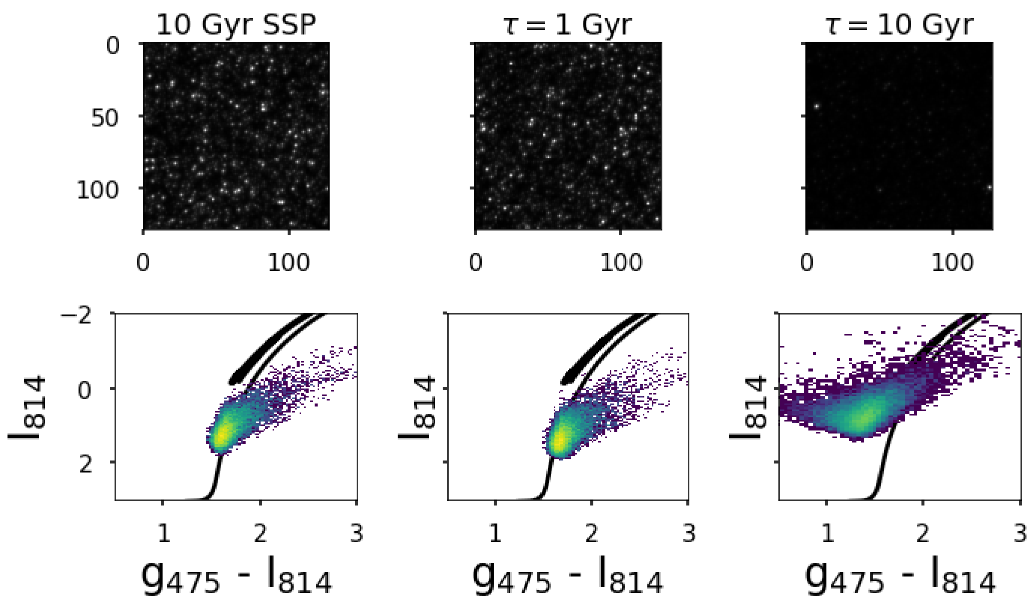


4.4 Star-Formation History

- Simplest model: SSP
- N_{pix} and age
- τ model: $SFR \sim \exp(-t/\tau)$
- N_{pix} and τ
- Non-Parametric model:
- Fit for N_{pix} in each age bin

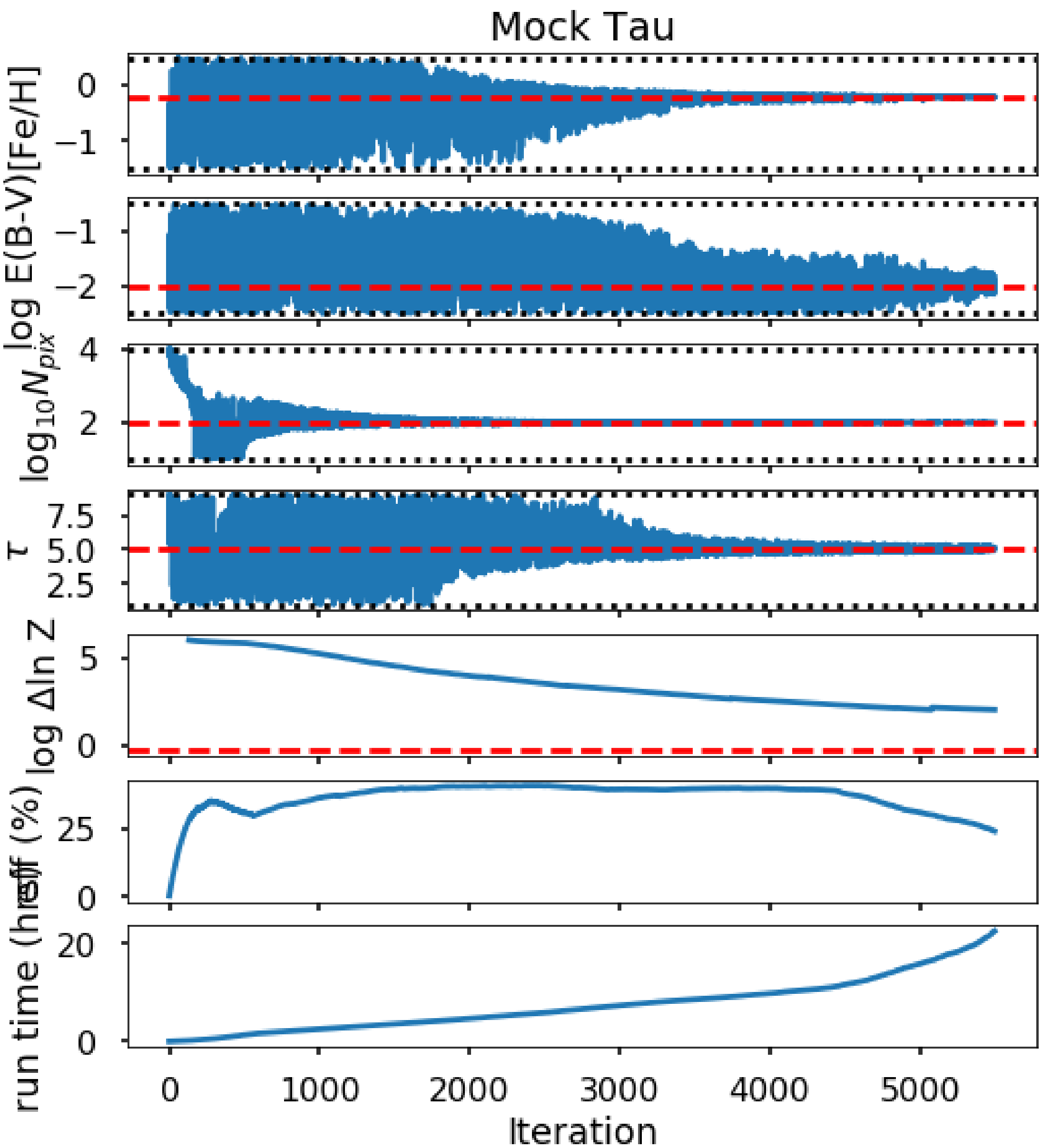
In [8]:
```
g1 = ppy.galaxy.DefaultSSP.get_model(np.array([0., -2., 2., 10.]), iso_step=-1)
g2 = ppy.galaxy.DefaultTau.get_model(np.array([0., -2, 2., 2.]), iso_step=-1)
g3 = ppy.galaxy.DefaultTau.get_model(np.array([0., -2., 2., 10.]), iso_step=-1)

pcmd1_s, im1_s = driv.simulate(g1, N_im)
pcmd2_s, im2_s = driv.simulate(g2, N_im)
pcmd3_s, im3_s = driv.simulate(g3, N_im)
```

```
In [35]: fig, a = plt.subplots(ncols=3, nrows=2, figsize=(10, 6), sharex='row', sharey='row')
         a[0,0].imshow(im1_s[0],cmap='Greys_r'),a[0,0].set_title(r'10 Gyr SSP')
         a[0,1].imshow(im2_s[0],cmap='Greys_r'),a[0,1].set_title(r'$\tau = 2$ Gyr')
         a[0,2].imshow(im3_s[0],cmap='Greys_r'),a[0,2].set_title(r'$\tau = 10$ Gyr')
         plot_pcmd(pcmd1_s, ax=a[1,0]),plot_pcmd(pcmd2_s,ax=a[1,1]),plot_pcmd(pcmd3_s,ax=a[1,2])
         a[1,0].set_ylim([3., -2.]),a[1,0].set_xlim([0.5, 3]), plt.tight_layout()

Out[35]: ((3.0, -2.0), (0.5, 3), None)
```

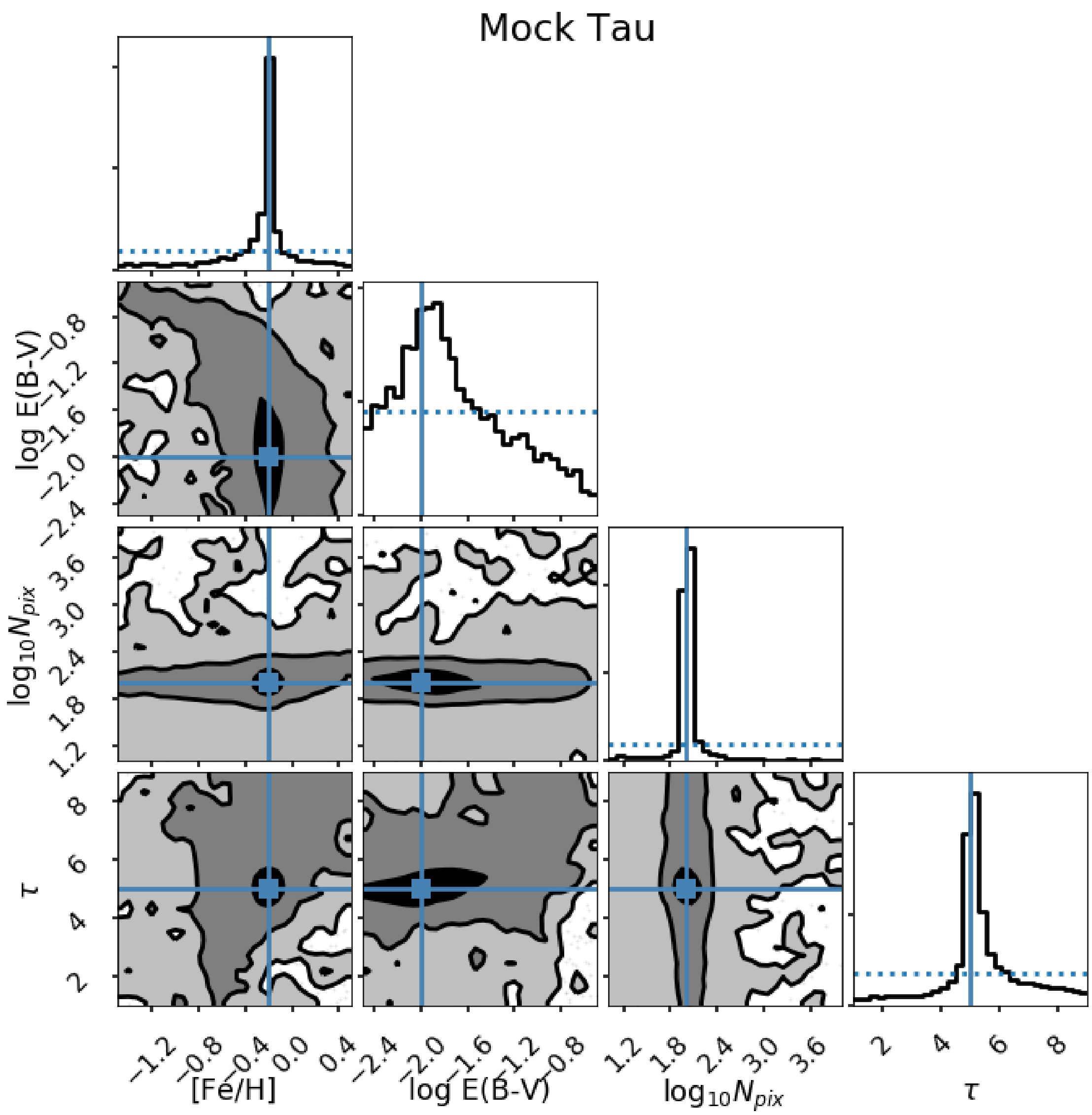


5 Fit Using Nested Sampling (Dynesty)

```
In [18]: res = {}
         t = ppy.galaxy.DefaultTau.get_model([-0.2, -2., 2., 5.])
         p = ppy.galaxy.DefaultTau.get_flat_prior([[-1.5, 0.5]], [[-2.5, -0.5]], [[1., 4.], [1.,
         res['base'] = ppy.utils.ResultsPlotter('../../scripts_py/results/mock_tau_nlive.csv',tr

In [19]: res['base'].plot_chains();
```




```
In [20]: res['base'].plot_corner(weight=False);
```



6 Testing against Complex Data