Project 1

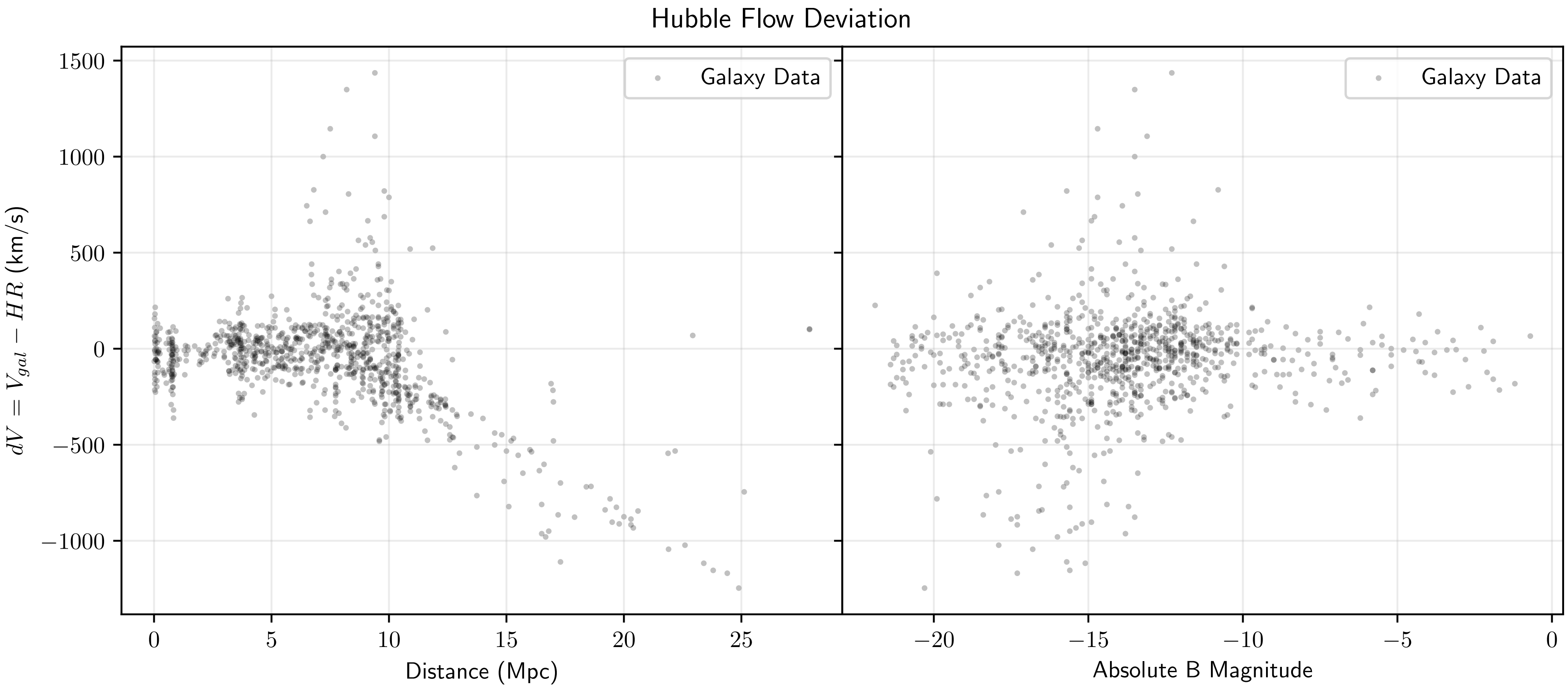
B. Connor McClellan

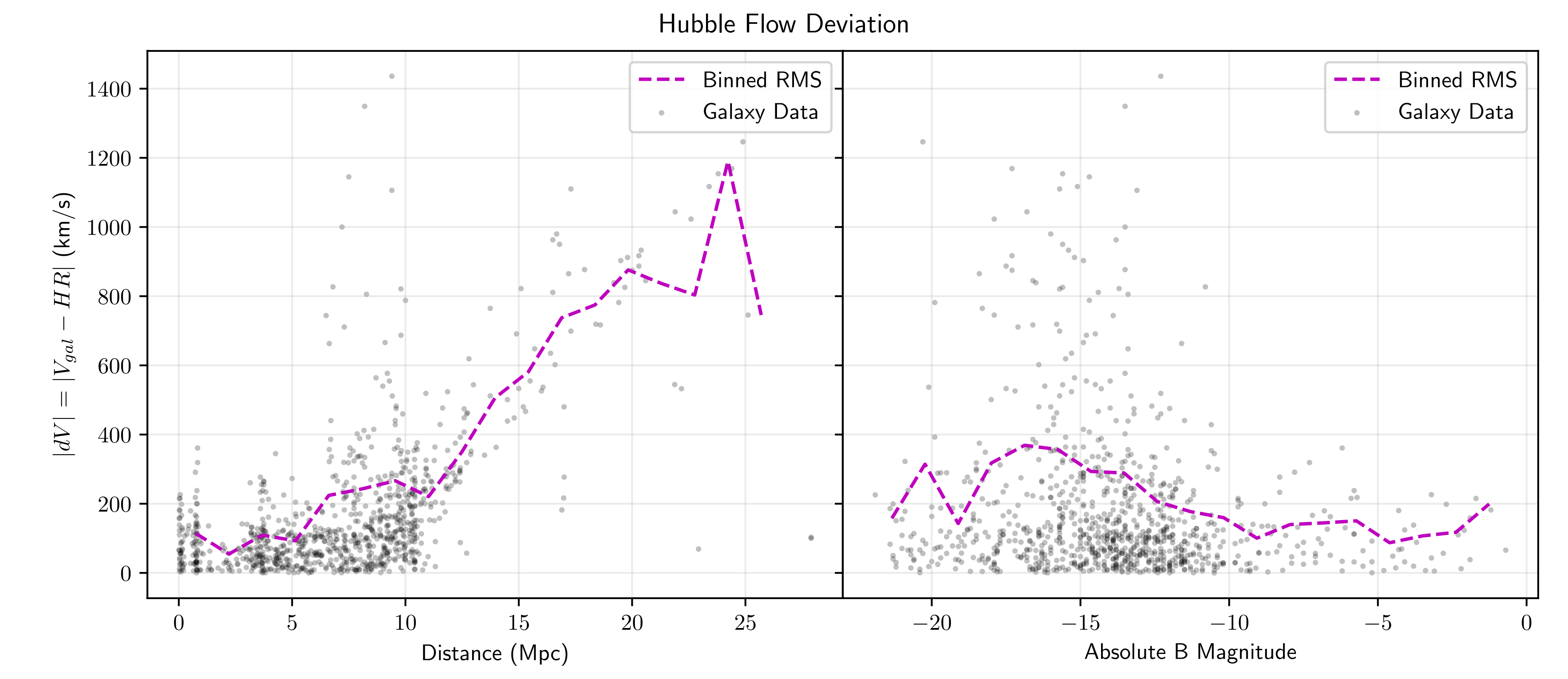
To characterize the Root Mean Square (RMS) deviation of line-of-sight galaxy velocities from the Hubble flow, it is necessary to bin these values based on both distance and absolute magnitude. These data are obtained from Karachentsev et al (2013). The deviation from the Hubble flow is $dV = V_{gal} - HR$, where H is the Hubble constant and R is the distance to the galaxy.

In Figure 1, I plot the values of dV for each galaxy in the catalog. It is seen that galaxies at large distances have a large negative deviation from the Hubble flow, meaning that their recessional velocity is smaller than predicted by the Hubble flow. In Figure 2, the left-hand plot shows the absolute value of the deviation, as well as the binned RMS ($\sqrt{\frac{1}{n}\sum x_i^2}$). 20 bins uniformly spaced in distance are used to obtain the trend.

On the right-hand side of Figure 1 and Figure 2, the same analysis is performed, but testing the dependence of the deviation on absolute magnitude instead. A relatively flat trend emerges from the data, indicating that there is less of a systematic dependence of the Hubble flow deviation upon magnitude.

This study calls into question the ability of the Hubble law to accurately predict line-of-sight velocities of galaxies, especially at large distances ($R >$ 10 Mpc).


Hubble Flow Deviation
Galaxy Data
Galaxy Data
$dV = V_{gal} - HR$ (km/s)
1500
1000
500
0
−500
−1000
0
5
10
15
20
25
Distance (Mpc)
−20
−15
−10
−5
0
Absolute B Magnitude


Hubble Flow Deviation
Binned RMS
Galaxy Data
$|dV| = |V_{gal} - HR|$ (km/s)
0
200
400
600
800
1000
1200
1400
0
5
10
15
20
25
Distance (Mpc)
Binned RMS
Galaxy Data
−20
−15
−10
−5
0
Absolute B Magnitude

```python
from astropy.io import ascii
import astropy.constants as c
import astropy.units as u
import matplotlib.pyplot as plt
import matplotlib
matplotlib.rcParams['text.usetex'] = True
import numpy as np

def rms(x):
    return np.sqrt(np.sum(x**2)/len(x))

# Load the tables
table1 = ascii.read('lvg_table1.dat')
table2 = ascii.read('lvg_table2.dat')

# Pick out data we actually need
v_gal = table2['VLG']
distance = table1['Dis']
mags = table2['BMag']

# Get rid of the masked values in the Column object
mask = ~(v_gal.mask ^ mags.mask)
v_gal = v_gal[mask]
distance = distance[mask]
mags = mags[mask]

# Calculate the deviation from the Hubble flow
H = 70. * u.Unit('km/(s * Mpc)')
dV = v_gal - H * distance

# Bin by distance or magnitude and calculate the RMS in each bin
def bin_data(indep_var):
    bins = np.linspace(min(indep_var), max(indep_var), 20)
    inds = np.digitize(indep_var, bins)
    rms_array = [rms(dV[inds == i]) for i in range(1, len(bins))]
    bincenters = (bins[:-1] + bins[1:])/2
    return bincenters, rms_array

dist_bins, dist_rms = bin_data(distance)
mag_bins, mag_rms = bin_data(mags)

fig, (ax1, ax2) = plt.subplots(1, 2, figsize=(8, 6), sharey=True)
ax1.scatter(distance, np.abs(dV), s=2, c='k', alpha=0.25, label='Galaxy Data')
ax1.plot(dist_bins, dist_rms, 'm--', label='Binned RMS')
ax1.set_xlabel('Distance (Mpc)')
ax1.grid(alpha=0.25)
ax1.legend()
ax1.set_ylabel('$|dV|$ = $|V_{gal} - HR|$ (km/s)')
ax2.plot(mag_bins, mag_rms, 'm--', label='Binned RMS')
ax2.scatter(mags, np.abs(dV), s=2, c='k', alpha=0.25, label='Galaxy Data')
ax2.set_xlabel('Absolute B Magnitude')
ax2.grid(alpha=0.25)
plt.suptitle('Hubble Flow Deviation')
plt.legend()
plt.tight_layout()
plt.subplots_adjust(top=0.925,
bottom=0.119,
left=0.094,
right=0.981,
hspace=0.,
wspace=0.)
plt.show()
```