ASTR469: Project #1, Green Bank H I Data!

Due 3 April by class time.
This project will focus your skills with the following concepts:
Radio astronomy; Spectroscopy; HI line emission; Doppler/gas dynamical effects;
Regression and error analysis; Unix; Python; LaTeX; Observing basics (coordinates, time).

We will have three in-class sessions (including this one) to work on this assignment. I am here to help. Class time will likely not be sufficient to complete all the analyses and the write-up.

Submission: Projects must be written in LaTeX using Overleaf (use documentclass *article*). Please produce a PDF and submit it to me either via email or hardcopy in class.

Description: The data are of M33, the Triangulum galaxy, taken by the ASTR469 class in Green Bank from when I taught this course in 2017. The data cover about $1° \times 1°$ across the galaxy. There is also a vertical stripe on the west (east and west are backwards in astronomy from what you're used to!) from a larger map we had planned but didn't have time to complete. We observed H I, atomic hydrogen, at 1420 MHz. The H I emission line is caused when the electron flips from spin-aligned with the proton to spin anti-aligned. There is a small change in energy associated with this change, which leads to a low-energy photon being emitted. Although this reaction is incredibly slow for a given H I atom, there is just so much H I out there that the line itself is strong. It is the most important line in all of astrophysics. The galaxy M33 is rotating so some of the hydrogen is coming towards us and some is going away, causing shifts in the observed frequency.

For this first project, I will provide a step-by-step guide. In future projects, you will be increasingly independent.

Project tasks:

1. **Download the data**:
   The data are located on the course website: "M33_CUBE_K.FITS"
   FITS files are a standard astronomical data format (FITS, Flexible Image Transport System). This is the format for nearly all 2D ("images") and 3D data ("cubes"), as well as for data with a higher number of dimensions as we will see for X-ray data in a later project. This file is a 3D data cube with two spatial axes (RA and Dec.) and one velocity axis. We created it by scanning the telescope across the galaxy — single-dish radio telescopes generally only observe a single spatial location. Each spatial location (called a "spaxel") has a spectrum and all those data are combined to make a data cube.

   The units for the cube data are "antenna temperature," in K. We discussed "brightness temperature" before; antenna temperature is related to brightness temperature by a constant set by the telescope and the observing frequency. We won't need this conversion, but labels on plots should be of antenna temperature. The velocity axis has units of m/s. The data were taken in frequency-space, and then converted to
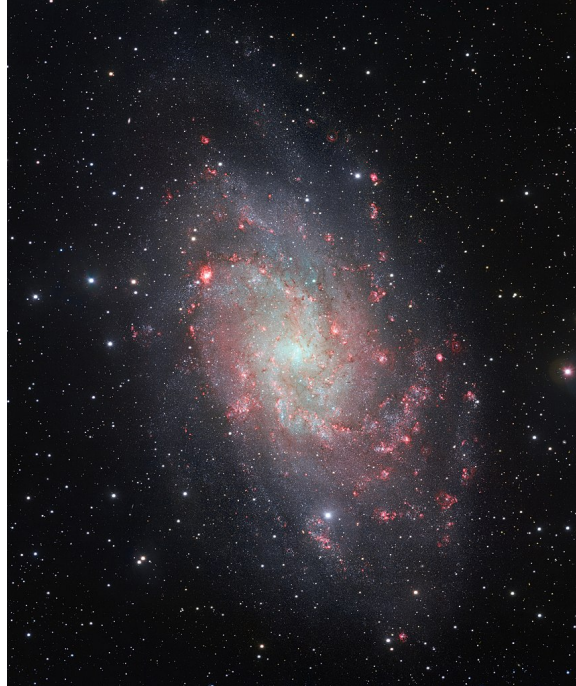
Figure 1: M33, the Triangulum galaxy. This is an optical image where massive star formation regions are in pink/red. A face-on galaxy would be circular, so the inclination is evident here.

velocity via the Doppler shift formula:

$$\frac{\Delta \nu}{\nu} = \frac{v}{c} \, . \tag{1}$$

Remember that negative velocities imply blue-shifted gas coming towards us ($\Delta\nu < 0$) and positive velocities imply red-shifted gas going away from us ($\Delta\nu > 0$).

2. **Image the data.** You can use a program called "DS9", which reads fits files. To get DS9, search for "DS9 astronomy" (otherwise you'll get Star Trek!).

   If you have loaded the file, the velocity slider allows you to step through different parts of the velocity axis. This allows you to view a 2D image at each velocity.

   You can also use the `astropy` package in Python to view the data. Take a look here: `https://docs.astropy.org/en/stable/io/fits/index.html`. To display "slice #50:"
   ```
   from astropy.io import fits
   import matplotlib.pyplot as plt
   hdu = fits.open('M33_CUBE_K.FITS')
   data = hdu[0].data
   plt.imshow(data[0,50,:,:])
   plt.show
   ```
   Note that the data are actually 4D, but the first dimension is redundant. Also, remember that python reverses the order when specifying array indices, so for us it's

[dummy, velocity slice, Dec, RA].
If we want astronomical coordinates, add:

```
from astropy.wcs import WCS
header = hdu[0].header
m33_wcs = WCS(header)
plt.subplot(projection=m33_wcs, slices=('x', 'y', 50, 0))
plt.imshow(data[0,50,:,:])
plt.show()
```

Which way is the galaxy rotating? **Make images showing the fastest receding H I gas and fastest approaching H I gas by varying the velocity slice. You will include these in your report. Be sure to note and label in your report the velocity of the images.**

If using DS9, by drawing and moving around a small region via click+drag, you also can see the spectrum of the galaxy in different localized spots in the galaxy. For this, first go to "Edit→ Region," then click somewhere to create a circular region, then double click within the region and go to "Analysis→ Plot 3D" in the dialog. You can replicate this in python by specifying an RA and Dec location: `plt.plot(data[0,:,50,50]` or, with units `ax = plt.subplot(projection=m33_wcs, slices=(50, 50, 'x',0))`

```
ax.plot(data[0, :, 50, 50])
plt.show()
```

3. **Produce a summed spectrum of the whole galaxy.** In DS9 you can draw a large region on the image; this will show you the summed spectrum from the entire data cube, thus giving you all the velocity data across the whole galaxy region. It should look familiar! We have seen similar spectra in class. Save this spectrum using the file menu in the spectrum display. This exports the spectrum as a text file. You can look at it on the command line:
   `>> less filename`
   In python, you can use `np.sum` to sum all RA and Dec values.

4. **Plot the spectrum in Python. You will also include this in your report.** If working from the DS9-created file, to import a space-delimited text file to a python list:
   `>> from numpy import genfromtxt`
   `>> M33spec = genfromtxt('filename',delimiter='')`
   `>> print(M33spec)`
   If you run this, it should print the spectrum data imported as a python list. The list is a 2D list (velocity, temperature); here is how you get a plot from a 2D python list, assuming you've imported matplotlib. This plots axis 0 on x-axis and axis 1 on y-axis:
   `>> plt.plot(M33spec[:,0],M33spec[:,1])`
   Remember your other python commands for plotting! **Produce a spectrum for your report — and be sure to add axis labels and units!**

5. **Analyze the spectrum.** The last formal lecture dealt with the basics of regression analysis. Include in your report a description of the main features of the spectrum you just plotted.

There should be two main velocity components, a broad component that is blue-shifted and a narrow component that is not. Where do these come from? It may help to look up M33 in Simbad (http://simbad.u-strasbg.fr/simbad/sim-fid) or NED (https://ned.ipac.caltech.edu/).

By eye, at what velocity range does M33 emit? What is the central velocity of M33 (estimate the center of the galaxy's distribution, or average your max and min line range values)? Compute the red/blue-shift of this galaxy based on the observed central velocity. Does your outcome agree with the (red/blue)-shift of M33 that you found previously in DS9 using the velocity slider?

6. **Determine the mass of M33.** In class, we spoke about how several effects can cause lines to not look perfect and narrow (gas is hot, galaxy is rotating so traveling at many different velocities, etc.). Estimate the width of the H I from M33 from your plot. Note that this galaxy is inclined compared to our line of sight, so the true velocity width of the galaxy (rather than the observed one) can be found with:

$$v_{\text{true}} = \frac{v_{\text{obs}}}{\sin(i)} \tag{2}$$

Where the inclination angle of Triangulum is $i = 55\,^\circ$.

For H I, there is a well-known relationship between the H I velocity width and the galaxy mass. It is called the "Tully-Fisher Relation" (Tully & Fisher, 1977). A plot of this is shown in Figure 2. Based on this plot, what is the mass of M33? Compare your value with the published value, which is around 50×10^9 solar masses (can check in Simbad or Ned again). Comment on any agreement/disagreement with respect to the size of any potential sources error in your result (ask yourself: where were estimations made, and what magnitude of error might a mis-estimation have produced?). Can you propagate the estimated measurement errors into mass errors?

7. Bonus: Moment Analyses. Humans work in 2D and have developed a number of different methods for visualizing 3D data, including a moment analysis. "Moment 0" is integrated intensity, essentially just smashing the cube down lengthwise. "Moment 1" is the intensity-weighted velocity. This is essentially the highest intensity velocity at east spatial location. I'll only give you broad contours here, but here is a code snipped to produce Moment 0:

```
from astropy.io import fits
hdu = fits.open('M33_CUBE_K.FITS')
data = hdu[0].data
M33_moment0 = np.sum(data[0,:,:,:], axis=0)
```
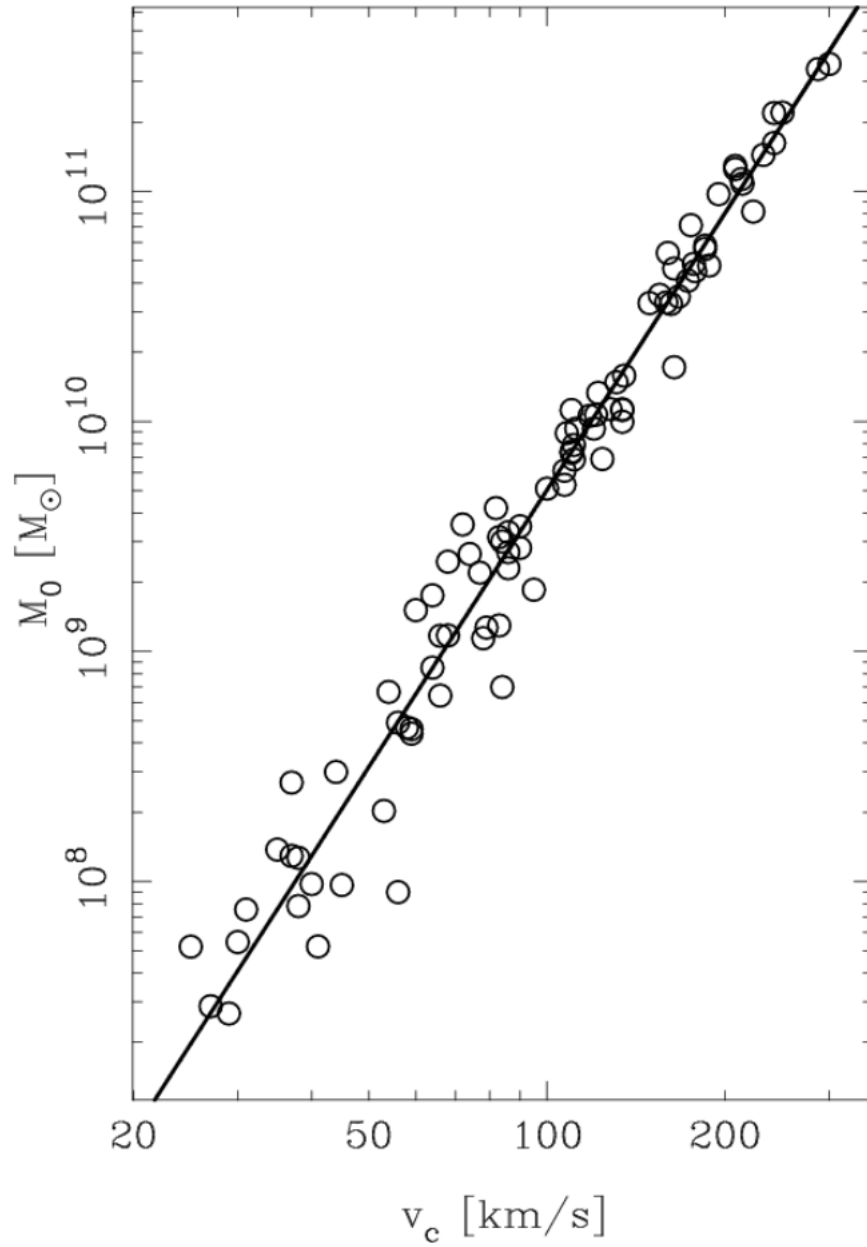
Figure 2: The Tully-Fisher relation that relates galaxy stellar mass to the H I velocity width of the galaxy. Here is a link to the paper if you'd like to read it (you can access the PDF if you're connected to WVU internet): http://adsabs.harvard.edu/abs/1977A%26A....54..661T

If you use this, be sure to understand what you are doing! What are the units of the 2D image? You can plot it in matplotlib. For Moment 1:

```
velocity = [create velocity array]
M33_moment1 = np.empty(shape=(128,128))
for i in range(128):
for j in range(128):
moment1[i,j] = np.sum(M33_data[0,:,i,j]*velocity[:], axis=0) / M33_moment0[i,j]
```

Same questions here!

8. **Write up your project (note: unfortunately you may have to be on the Windows side of the machines to use Overleaf, so you may need a thumb drive to transfer the files over – or just email them to yourselves. Or just use a personal computer.** Your write-up should include basic observation details (the target, its coordinates, the observing date of March 13, 2015, the telescope, frequency, etc.). Like any real astronomical publication, the write-up should generally describe your process: include relevant equations and figures with captions (I've noted in bold in the above which figures I expect to appear, at a minimum). Include sections like *Introduction, Observations/Data, Analysis/Results/Conclusions* (create your narrative as you see fit). A strong narrative tells the analysis steps but excludes extraneous details ("then I opened DS9 and then I selected Edit→region and then I drew a region and then I got a burrito from Chipotle....").

Interpret the results to the best of your ability. Don't worry overly about LaTeX formatting for this assignment; I will mostly grade on whether you included all the components above and the correctness of what you write. We can work on making things pretty for later assignments. For the ambitious: optional bonus points will be given for additional creative analysis insights and properly using LaTeX citations. **Excluding figures, a suitable length for the words in this project in \documentclass{article} format would be 1–2 pages.** Before you turn in your project, ask yourself:

- Did I include at least plots of the full spectrum, and at least two galaxy velocity images?

- Do my plots actually show up in the compiled Overleaf pdf file?

- Did I address all questions asked in each point above?

- Did I include an equation for at least the redshift calculation that I did?

- And perhaps most importantly, could someone following my methods reproduce the analysis?