Galactic Structure Continuous Assessment 1

Brendan Watters, 21363451

September 24, 2023

1 Introduction

This assignment was carried out with the NE2001 electron density model, using the pyne2001 Python package.

2 Line of sight

Based on the question, the initial line of sight chosen was (45.1°, 15°), and the second sight line was (45.1°, 25°) (all using Galactic Coordinates). As the Milky Way is estimated to be between 40 kpc and 50 kpc in diameter and the Sun is approximately 8 kpc from the centre [1] the distance used in the calculation of question 3 was 33 kpc. As the radius has a maximum value of 25 kpc according to this estimation, and adding the 8 kpc due to the Sun's position leads to a maximum distance to the outer edge of the Galaxy of 33 kpc (through the centre of the Galaxy, which of course is not the case here).

3 Max dispersion due to Milky Way

After running the code, the maximum dispersion that could be due to the Milky Way through the line of sight along (45.1°, 15°) is calculated to be 113.7071 pc cm^{-3}. At a further 10° from the Galactic plane, along the line through (45.1°, 25°) the maximum dispersion due to the Milky Way is 64.0221 pc cm^{-3}.

4 Dispersion as a function of distance

Using matplotlib the dispersion (in pc cm^{-3}) was plotted from a distance of 0.1 kpc to 50 kpc with a step size of 0.1 kpc through both sight lines. Two graphs were generated, one with a linear scale on both axes, and another with a logarithmic scale on the distance axis to better see the behaviour at small distances from the Earth. A CSV of the data was also generated and outputted.

As can be seen in figures 1 and 2 for the line of sight along (45.1°, 15°) the dispersion measure increases very little at distances greater than ∼11 kpc (see point A in the figures) and stops increasing entirely beyond 20.95 kpc (see point C in the figures). For the line along (45.1°, 25°) these observations can be made of distances much closer to the Earth, with very little increase beyond ∼7 kpc (see point B in the figures) and no increase at all beyond 14.56 kpc (see point D in the figures). It is likely that beyond those distances in these directions either the Galaxy has been left behind.

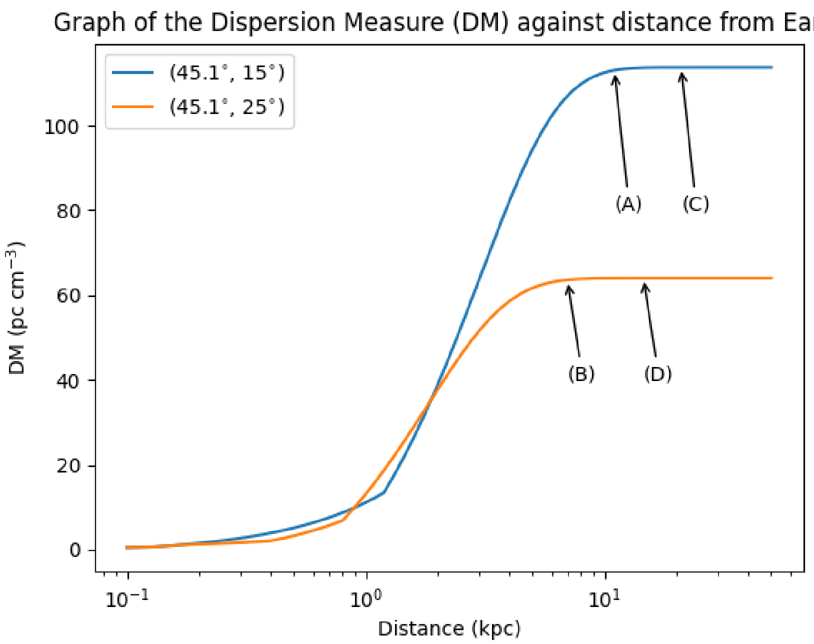

Figure 1: The graph of the dispersion measure as a function of distance along two lines of sight chosen, (45.1°, 15°) and (45.1°, 25°). The DM increases very slowly at distances greater than ∼11 kpc (point A) or beyond ∼7 kpc (point B along the respective sight lines. The DM also does not increase beyond point C (20.95 kpc, 113.7071 pc cm^{-3}) or point D (14.56 kpc, 64.0221 pc cm^{-3}) for both lines of sight respectively.

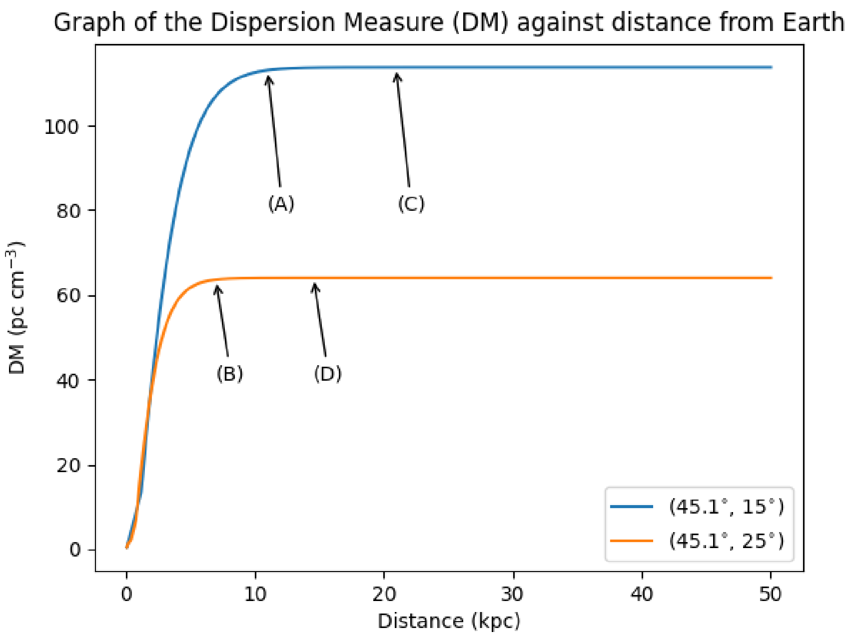

Figure 2: This graph displays the same information as figure 1 on a linear scale. This representation more easily displays the sharp increase at relatively close distances followed by a long continuous plateau with no increase in DM.

5 H I column density

The column density of neutral hydrogen is defined as

$$N_H = 10 \int_0^d n_e dl \tag{1}$$

where N_H is the column density of hydrogen, n_e is the number density of electrons and d is the distance from Earth.[2] The factor of 10 comes from the assignment stating that there is one electron for every ten hydrogen atoms.

The assignment also states that

$$DM = \int_0^d n_e dl \tag{2}$$

which leads to the final equation

$$N_H = 10DM \tag{3}$$

which currently would give a figure with units of pc cm^{-3}. As such the quantity must be converted to cm^{-2}. The conversion rate is 1 pc = 3.086×10^{19} cm. The graphs in figures 3 and 4 show the increase of the cumulative neutral hydrogen column density through the Galaxy.

The maximum H I density through the Galaxy is 3.51×10^{22} cm^{-2} along the line (45.1°, 15°), and 1.94×10^{22} cm^{-2} cm^{-2} along the line (45.1°, 25°).

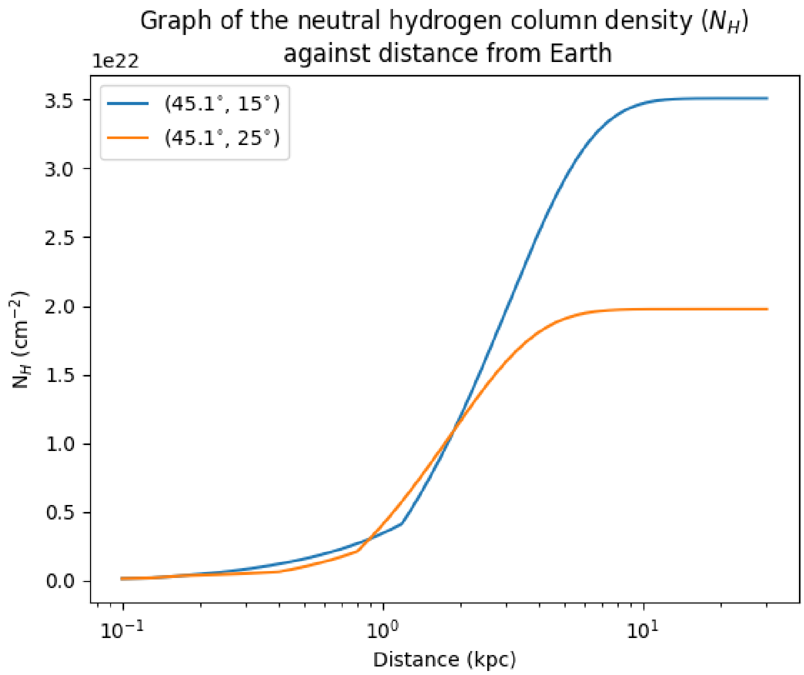

Figure 3: The graph of the cumulative H I column density as a function of the distance from the Earth along the sight lines (45.1°, 15°) and (45.1°, 25°) through the Galaxy.

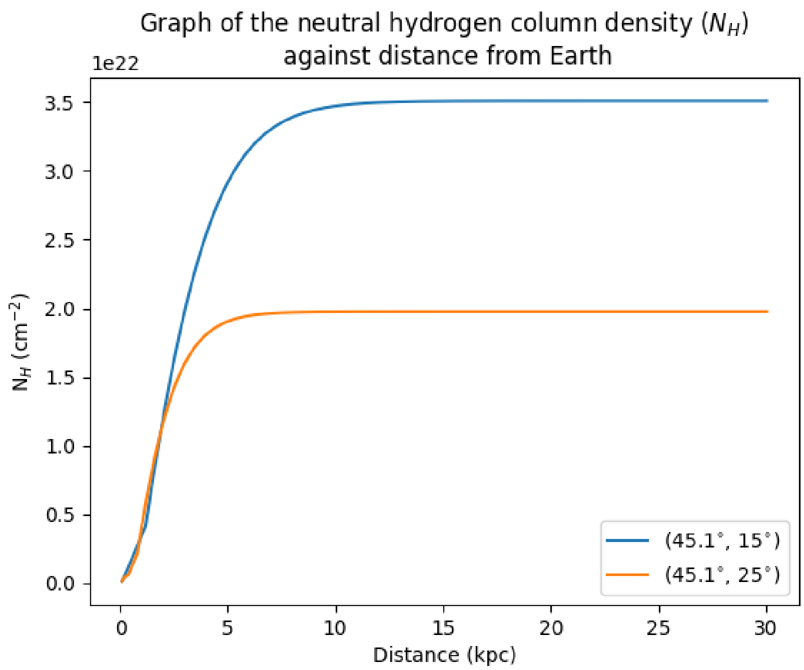

Figure 4: This graph displays the same information as figure 3 on a linear scale. This representation more easily displays the sharp increase at relatively close distances followed by a long continuous plateau with no increase in N_H.

6 $\frac{d}{dx}$ of the dispersion measure

In order to calculate the derivative of the dispersion measure with respect to distance (x) the DM of the region between 0.9 kpc and 1.1 kpc from Earth was calculated along both lines of sight. The derivative of the DM in that region was then calculated numerically via the central differences method. A plot was made of this data (see figure 5) and the data was also outputted to a spreadsheet to better determine the exact derivative at the point $x = 1kpc$.

As taken from the generated csv file the derivative of the dispersion measure at a distance of 1 kpc from Earth along the line (45.1°, 15°) is 12.0 pc cm^{-3} kpc^{-1} = 0.0120 cm^{-3}, and along the line (45.1°, 25°) at the same distance the derivative is found to be 0.0301 cm^{-3}.

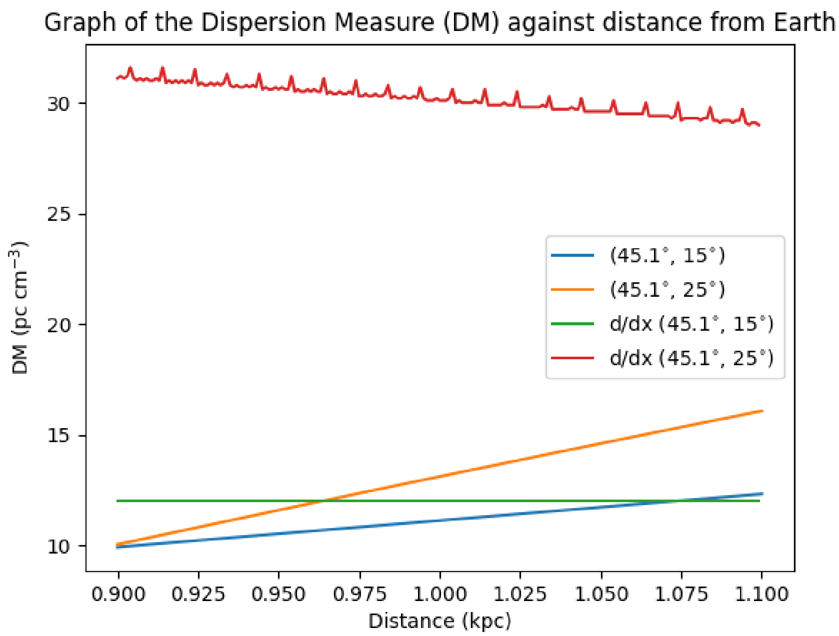

Figure 5: The values of the DM over the distance 0.9 kpc to 1.1 kpc from Earth along the lines (45.1°, 15°) and (45.1°, 25°), as well as the derivatives of these lines. While the derivatives of both are positive they are decreasing with distance. The spikes in the red line, the derivative of the DM when measured along the line (45.1°, 25°), are likely artefacts of the small step size, as the possibility of there being many regularly spaced gas clouds is very small and I am not aware of any other possible cause of these regularly placed spikes.

7 Extinction in the optical

The relation between N_H and optical extinction (A_V) is

$$N_H = 2.21 \times 10^{21} A_V \tag{4}$$

or

$$A_V = \frac{N_H}{2.21 \times 10^{21}} \tag{5}$$

with N_H measured in cm^{-2} and A_V expressed in magnitudes. Using this relation the optical extinction was calculated from the neutral hydrogen density and graphed out to the edge of the Galaxy as shown in figures 6 and 7.

From these graphs the maximum optical extinction along the lines of sight (45.1°, 15°) and (45.1°, 25°) are 15.9 magnitudes and 8.94 magnitudes respectively.

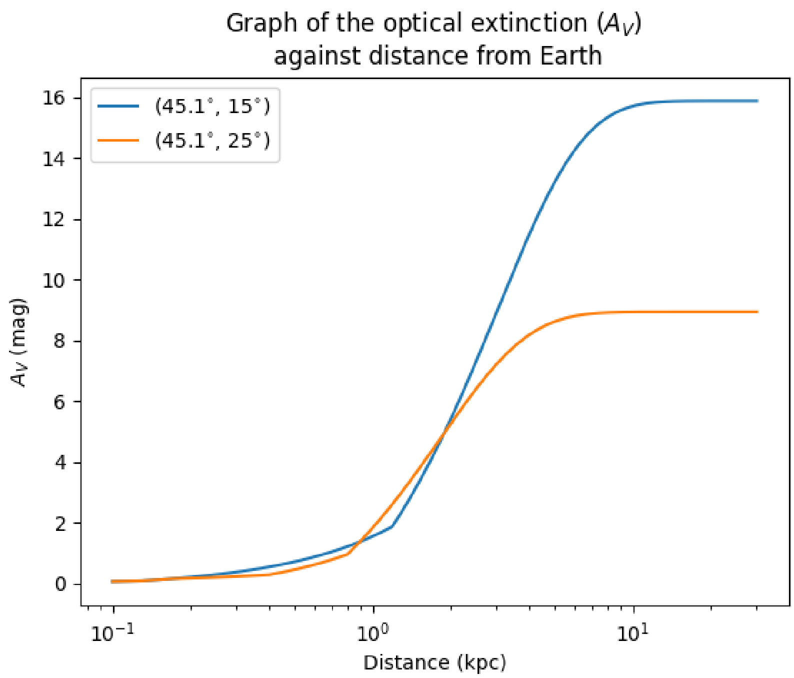

Figure 6: The graph of the extinction in the optical as a function of distance from the Earth along the lines of sight, (45.1°, 15°) and (45.1°, 25°) through the Galaxy.

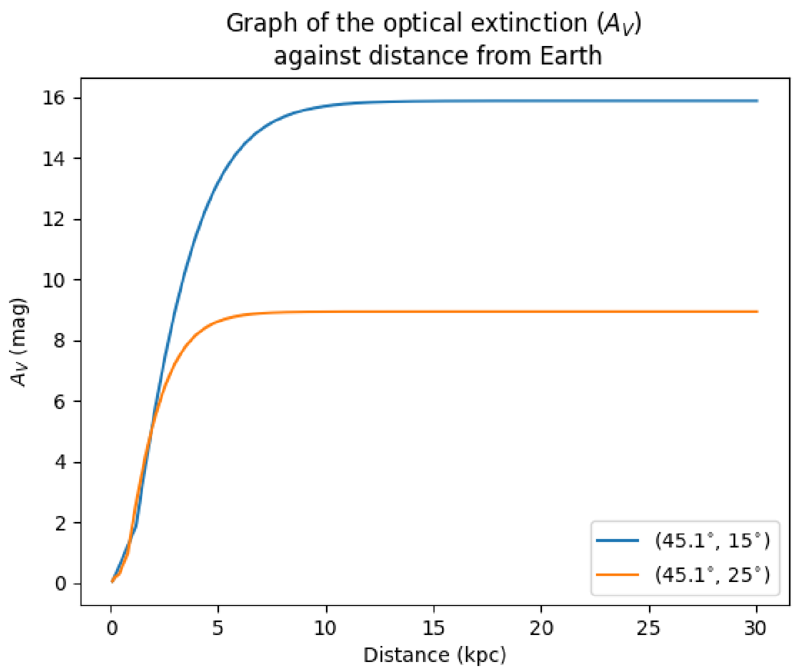

Figure 7: This graph displays the same information as figure 6 on a linear scale. This representation more easily displays the sharp increase at relatively close distances followed by a long continuous plateau with no increase in A_V.

8 Code

The code used in this assignment is found below.

```
# -*- coding: utf-8 -*-
import pyne2001 as ne
import numpy as np
import matplotlib.pyplot as plt

##################
#                #
#   Question 3   #
#                #
##################

# DM at the angles and up to 33 kpc away
max_dm1 = ne.get_dm(45.1, 15, 33)
max_dm2 = ne.get_dm(45.1, 25, 33)

print("The max DM due to the Galaxy along the line (45.1\u00b0, 15\u00b0) is " + str(max_dm1) + " pc cm\u207b\u00b3")
print("The max DM due to the Galaxy along the line (45.1\u00b0, 25\u00b0) is " + str(max_dm2) + " pc cm\u207b\u00b3")

```

```
#################
#               #
#   Question 4  #
#               #
#################

# Distance array - up to 50 kpc away
dist = np.arange(0.1, 50.01, 0.01)

# Arrays for results
dm1 = np.array([])
dm2 = np.array([])

for i in dist:
    dm1 = np.append(dm1, ne.get_dm(45.1, 15, i))
    dm2 = np.append(dm2, ne.get_dm(45.1, 25, i))

plt.plot(dist, dm1, label="(45.1$^{\circ}$, 15$^{\circ}$)")
plt.plot(dist, dm2, label="(45.1$^{\circ}$, 25$^{\circ}$)")

plt.legend()
plt.xlabel("Distance (kpc)")
plt.ylabel("DM (pc cm$^{-3}$)")
plt.title("Graph of the Dispersion Measure (DM) against distance from Earth")
plt.annotate('(A)', xy=(11,113.0185), xytext=(11,80), arrowprops=dict(arrowstyle="->"))
plt.annotate('(B)', xy=(7,63.6131), xytext=(7,40), arrowprops=dict(arrowstyle="->"))
plt.annotate('(C)', xy=(20.95,113.7071), xytext=(21,80), arrowprops=dict(arrowstyle="->"))
plt.annotate('(D)', xy=(14.56,64.0221), xytext=(14.5,40), arrowprops=dict(arrowstyle="->"))

# Save linear scaled graph
plt.savefig("dispersion_graphs.png")

# Make a log graph also
plt.xscale('log')
plt.savefig("dispersion_graphs_log.png")

# Close figures
plt.close()

# Output a CSV of the DMs and distances
output_Q4 = np.array([dist, dm1, dm2])
output_Q4 = np.transpose(output_Q4)
np.savetxt("output_Q4.csv", output_Q4, delimiter=",")

#################
#               #
#   Question 5  #
#               #
#################

# Convert from pc cm^-3 to cm^-2

max_density_H_1 = max_dm1 * 3.086 * 10**20
max_density_H_2 = max_dm2 * 3.086 * 10**20

```

```
# Also limit to approx 30 kpc
density_H_1 = dm1[0:int(np.floor(len(dm1)*3/5))] * 3.086 * 10**20
density_H_2 = dm2[0:int(np.floor(len(dm2)*3/5))] * 3.086 * 10**20

print("The H I density to the edge of the galaxy along the line (45.1\u00b0, 15\u00b0) is " + str(max_density_H_1) + " cm\u207b\u00b2")
print("The H I density to the edge of the galaxy along the line (45.1\u00b0, 25\u00b0) is " + str(max_density_H_2) + " cm\u207b\u00b2")

plt.plot(dist[0:len(density_H_1)], density_H_1, label="(45.1$^{\circ}$, 15$^{\circ}$)")
plt.plot(dist[0:len(density_H_2)], density_H_2, label="(45.1$^{\circ}$, 25$^{\circ}$)")

plt.legend()
plt.xlabel("Distance (kpc)")
plt.ylabel("N$_H$ (cm$^{-2}$)")
plt.title("Graph of the neutral hydrogen column density ($N_H$) \n against distance from Earth")

# Save linear scaled graph
plt.savefig("density_graphs.png")

# Make a log graph also
plt.xscale('log')
plt.savefig("density_graphs_log.png")

# Close figures
plt.close()

#################
#               #
#   Question 6  #
#               #
#################

# Distance array - 0.9 to 1.1 kpc away
dist_derivative = np.arange(0.9, 1.1, 0.001)

# Arrays for DMs
dm1 = np.array([])
dm2 = np.array([])

for i in dist_derivative:
    dm1 = np.append(dm1, ne.get_dm(45.1, 15, i))
    dm2 = np.append(dm2, ne.get_dm(45.1, 25, i))

plt.plot(dist_derivative, dm1, label="(45.1$^{\circ}$, 15$^{\circ}$)")
plt.plot(dist_derivative, dm2, label="(45.1$^{\circ}$, 25$^{\circ}$)")

# Arrays for derivatives
ddm1 = np.array([])
ddm2 = np.array([])

i = 0
while i < len(dist_derivative) - 1:
    ddm1 = np.append(ddm1, (dm1[i+1] - dm1[i])/(0.001))
    ddm2 = np.append(ddm2, (dm2[i+1] - dm2[i])/(0.001))
```

```
    i += 1

plt.plot(dist_derivative[:-1], ddm1, label="d/dx (45.1$^{\circ}$, 15$^{\circ}$)")
plt.plot(dist_derivative[:-1], ddm2, label="d/dx (45.1$^{\circ}$, 25$^{\circ}$)")

plt.legend()
plt.xlabel("Distance (kpc)")
plt.ylabel("DM (pc cm$^{-3}$)")
plt.title("Graph of the Dispersion Measure (DM) against distance from Earth")

# Save graph
plt.savefig("derivative_graphs.png")
plt.close()

# Output a CSV of the derivatives and distances
# Append a 0 to give it the same size as dist
ddm1 = np.append(ddm1, 0)
ddm2 = np.append(ddm2, 0)

output_Q6 = np.array([dist_derivative, ddm1, ddm2])
output_Q6 = np.transpose(output_Q6)
np.savetxt("output_Q6.csv", output_Q6, delimiter=",")

##################
#                #
#   Question 7   #
#                #
##################

# Convert from pc cm^-3 to cm^-2

max_extinction_1 = max_density_H_1 / (2.21 * 10**21)
max_extinction_2 = max_density_H_2 / (2.21 * 10**21)

# Also limit to approx 30 kpc
extinction_1 = density_H_1 / (2.21 * 10**21)
extinction_2 = density_H_2 / (2.21 * 10**21)

print("The optical extinction to the edge of the galaxy along the line (45.1\u00b0, 15\u00b0) is " + str(max_extinction_1) + " magnitudes")
print("The optical extinction to the edge of the galaxy along the line (45.1\u00b0, 25\u00b0) is " + str(max_extinction_2) + " magnitudes")

plt.plot(dist[0:len(extinction_1)], extinction_1, label="(45.1$^{\circ}$, 15$^{\circ}$)")
plt.plot(dist[0:len(extinction_2)], extinction_2, label="(45.1$^{\circ}$, 25$^{\circ}$)")

plt.legend()
plt.xlabel("Distance (kpc)")
plt.ylabel("$A_V$ (mag)")
plt.title("Graph of the optical extinction ($A_V$) \n against distance from Earth")

# Save linear scaled graph
plt.savefig("extinction_graphs.png")

# Make a log graph also
plt.xscale('log')
```

```python
plt.savefig("extinction_graphs_log.png")

# Close figures
plt.close()
```

References

[1] B. W. Carroll, D. A. Ostile, *An Introduction to Modern Astrophysics*, 2nd ed. Harlow, England: Pearson: 2014

[2] G. Visconti, *Fundamentals of physics and chemistry of the atmosphere*. Berlin: Springer: 2001