PEU 327 – Spring 2025
Observatinal Astrophysics Laboratory

Lab 4 Manual

Physics of Universe (PU) Program
University of Science and Technology at Zewail City

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Galaxy Photometric Populations, Structure, & Stellar Kinematics

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[1] Please state explicitly in your report the tasks performed by each group memeber.

<u>Grading sheet</u>

Student Name ------------------------------

Student ID ------------------------------

Item	*Grade*	*Maximum*
Experiment VII		20
Experiment VIII		20
Jupyter Notebook[2]		**10**
Total		**50**

TA Signature:

[2]This Lab should be submitted as a Jupyter Notebook file or its PDF version which includes your codes/work, output/results, and answers/discussion. (Please do not submit a Google Colab link.) A LaTeX report could be alternatively submitted as long as it comprehensively and neatly shows your work.

Experiment (VII)

Stellar Kinematics of 300,000 Stars in the Milky Way Galaxy

Introduction

In this experiment, you will study the the observational properties of about 300,000 stars obtained recentrly with ESA's billion star surveyor, Gaia spacecraft.

Gaia

Since lanched in 2013, Gaia spacecraft is creating an extraordinarily precise three-dimensional map of more than a thousand million stars throughout our Milky Way galaxy and beyond, mapping their motions, luminosity, temperature and composition. This huge stellar census will provide the data needed to tackle an enormous range of important questions related to the origin, structure and evolutionary history of our galaxy.

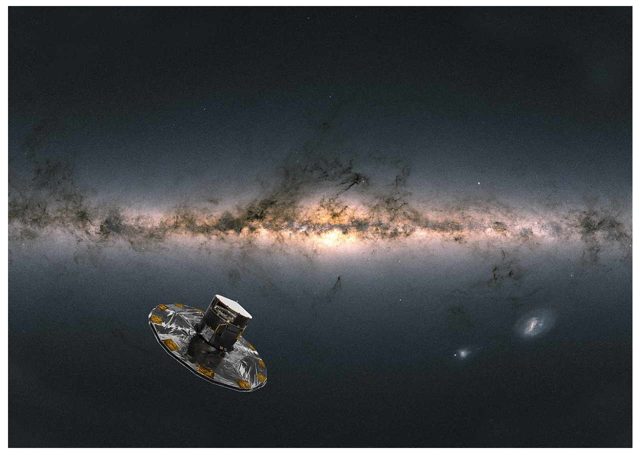

Figure 1: Gaia Spacecraft

Procedures

For the purpose of this experiment, download the attached Gaia dataset of proper motions and distances for stars with parallaxes >5 milliarcsec that also live within 10 degrees of the disk plane — Gaia_bLT10_pGT5.fits. It is big enough that its best to store it in a binary Flexible Image Transport System (FITS) data format. The `astropy` package has a `read()` method for reading and parsing such files into an astropy `Table`.

```
pip install astropy
from astropy.table import Table

filename = "Gaia_bLT10_pGT5.fits"
gaia_data = Table.read(filename)
```

Tip: If the FITS file is not in the same directory as the Python active environment, include the full filepath in the `filename` variable. Also, `astropy` need not be installed if it was previously installed in said environment.

There are close to 300,000 stars in that database; hence, attributes like `colnames` or `info` can be used to view the contents of `astropy.table.Table` class.

```
gaia_data.info
```

Out [2]:

```
<Table length=291961>
      name        dtype    unit                     description                       class
--------------- ------- -------- ------------------------------------------- ------------
             ra float64      deg                             Right ascension       Column
            dec float64      deg                                 Declination       Column
       parallax float64      mas                                    Parallax       Column
           pmra float64 mas / yr Proper motion in right ascension direction       Column
          pmdec float64 mas / yr     Proper motion in declination direction       Column
phot_g_mean_mag float32      mag                        G-band mean magnitude       Column
          bp_rp float32      mag                               BP - RP colour       Column
              l float64      deg                                                    Column
              b float64      deg                                                    Column
            pml float64                                                             Column
            pmb float64                                                             Column
      star_type   int64                                                       MaskedColumn
```

The later columns without descriptions are coordinates in Galactic longitude (l) and latitude (b); proper motions ($^{\text{milliarcsec}}/_{\text{yr}}$) along l and b; and a custom coding: 1 = Main Sequence (MS) star, 2 = red giant, 3 = white dwarf, 0 = other; respectively.

Your First Task:

1. Calculate the distance (in parsecs) to each star using the trigonometric parallax method — 1 column.

2. Deduce the absolute magnitude (M_G) from the apparent G-band magnitude (m_G) using the Magnitude-Distance formula — 1 column.

Now, make a Color Magnitude Diagram (CMD) of the resulted M_G vs the BP-RP color column in the dataset using the following code snippet which accounts for the large number of stars in the plot that can overwhelm the plotting area.

```
pip install matplotlib
import matplotlib.pyplot as plt
from matplotlib.colors import LogNorm

cmd_res = (np.linspace(-0.75,3.5,151), np.linspace(-3, 17, 201))

fig = plt.figure(figsize=(5,5))
ax = fig.add_subplot(111)
h = ax.hist2d(gaia_data['bp_rp'], MG, bins=cmd_res, norm=LogNorm(1.0,1e3))
cb = fig.colorbar(h[3])
cb.ax.minorticks_off()
ax.invert_yaxis()
ax.set_xlabel('BP-RP Color')
ax.set_ylabel('Abs G Mag')
ax.set_yticks(np.arange(-2, 18, 2))
ax.scatter(0.82, 4.67, color='orange', edgecolor='#661100', s=20, lw=1)
```

Note: The two variables `bp_rp` and `MG` are the BP-RP color and M_G, respectively. Also, import NumPy if you had not already to be able to use its `linspace()` method.

Your Second Task:

3. Determine each star's W velocity ($^{\mathrm{km}}/_{\mathrm{s}}$) – the velocity up/down out of the galactic plane (i.e., $\frac{\mathrm{dz}}{\mathrm{d}t}$ where z is the perpendicular distance from the plane) – using the distance and the proper motion along the b direction.

4. For each of the following star samples: All MS stars, Red-Giant Branch (RGB) stars, blue MS stars (BP-RP < 0.5):

   (a) Plot a histogram of the W velocities for each sample (set your histogram to have 50 bins running from $W = -75\,^{\mathrm{km}}/_{\mathrm{s}}$ to $+75\,^{\mathrm{km}}/_{\mathrm{s}}$)

   (b) Find the Sun's W velocity (non-zero mean velocity) and the velocity dispersion of the stars in the sample (standard deviation).

Tip: Either carry out the calculations data wide and select the intended rows using a Boolean expression or use the loc property[3] to segregate the aforementioned star samples before the analysis.

5. Provide a good discussion of why the values are different or not between such samples.

Comments:

[3] Convert `gaia_data` to a pandas Dataframe first because `astropy.table.Table.loc` cannot return a TableLoc object without single-column indices.

Experiment (VIII)

The Vertical Structure of the Milky Way's Galactic Disk

Introduction

In this Experiment, we will study the structural properties of thin disk of the Milky way galaxy, in particular, we focus on computing the scale height of the thin disk using Gaia space observatory data. In principle, a scale height is a distance (vertical or radial) over which a physical quantity decreases by a factor of e (the base of natural logarithms). The thin disk is a structural component of spiral and S0- type galaxies, composed of stars, gas and dust. It is the main non-centre (e.g., galactic bulge) density of such matter. That of the Milky Way is thought to have a scale height of around 300–400 parsecs (980–1,300 ly) in the vertical axis perpendicular to the disk, and a scale length of around 2.5–4.5 kiloparsecs (8.2–14.7 kly) in the horizontal axis, in the direction of the radius. For comparison, the Sun is 8 kiloparsecs (26 kly) out from the center.

The thin disk contributes about 85% of the stars in the Galactic plane and 95% of the total disk stars as seen in figure 2. It can be set apart from the thick disk of a galaxy since the latter is composed of older population stars created at an earlier stage of the galaxy formation and thus has fewer heavy elements. Stars in the thin disk, on the other hand, are created as a result of gas accretion at the later stages of a galaxy formation and are on average more metal-rich.

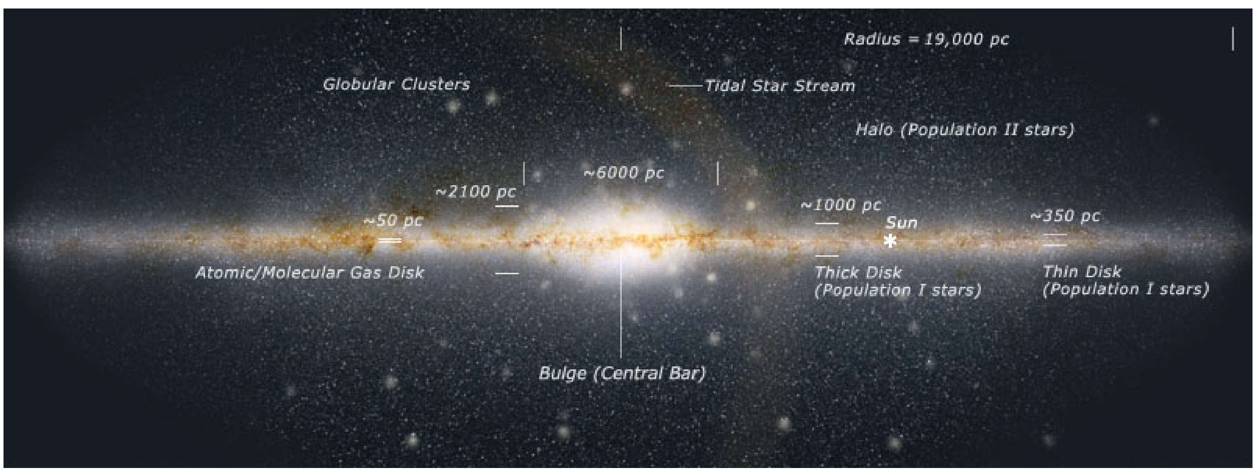

Figure 2: The Milky Way Structure

In this experiment, you are going to compute the scale height of the thin disk using Gaia data.

Discussion Question: If the density of stars is of an exponential form like $\rho \approx e^{-z/h_z}$, how would the slope of the line relate to the scale height h_z when you plot $\log_{10} \rho$ vs z?

Procedures

Another Gaia dataset, Gaia_NSGP.fits, for stars within 10 degrees of the North or South Galactic Pole (i.e., straight up or down out of the disk) is attached as well. It is not required that they be within 200 pc of the Sun, but we do make sure they have good parallaxes. So, there is no hard distance limit in this dataset, but faint stars drop out of the sample because it is hard to get a good parallax for faint stars.

Your First Task: Repeate the same procedures as in Task 1 in Exp.VII : Read the new file, calculate the distance and M_G, and plot the M_G vs BP-RP color CMD.

Your Second Task: You should be able to spot red clump stars (a cluster of metal-rich, hot red giants) in your CMD; what is its absolute magnitude? Then select RGB stars which have an absolute magnitude within 0.5 mag of the clump center as your red clump sample.

Use the following code snippet to count the number of stars in 1) the MS and 2) the RGB red clump in bins of distance, and convert that into a density of stars as function of distance from the plane.

```
N, edges = np.histogram(distance, bins=100, range=[0,4000])
vol = (4*np.pi/3) * edges**3
dvol = np.diff(vol)
logdens = np.log10(N/dvol)
bincent = 0.5*(edges[1:]+edges[:-1])
plt.scatter(bincent, logdens)
```

1. In your lab report, explain every line of code in this snippet.
2. Fit a straight line to the data for bins $\leq$ 1 kpc distant, where the thin disk dominates.
3. Given the parameters of the fit, overplot it on your data, and use it to derive the thin disk scale height.

After you have done that for each sample, compare the two numbers (the scale heights for the all MS stars sample and the red clump stars). How well do they compare to each other? The red clump stars should give a better estimate for the scale height than the MS sample. Explain why. Think about the luminosity spread of the two samples, and how that connects to the numbers of stars you observe as a function of distance. How well does your fit work over the whole range of distances on your plot (not just where you fit)? Lastly, explain any differences you see between your fit and the shape of the data points.

Comments: