PHYS 4720/6720 - Galaxies and the ISM
Prof. Cara Battersby, Spring 2023

Instructions:

- Please include your name, who you worked with, any resources you used on the first page of your submitted problem set.
- This problem set includes a coding problem set in Google Colab and this Written Problem Set. Please complete all cells in that colab notebook, save it as 'LastName_PS2_Coding.ipynb' and share with me on Google.
- Please either write up (very neatly!) or typeset the written problem set. If typeset, please save as 'LastName_PS2_written.pdf'. You can bring a written or printed copy to class or I will have a folder in our shared google drive where you can 'hand in' your PDF file electronically at the start of class.
- The first page of your written PDF should **include your name, who you worked with, any resources you used, and the total number of hours you spent (including reading, group discussion, individual work, writeup) on this problem set.**

General advice and reminder on submitting professional assignments for this class.

1. Your written work must be **highly legible or typeset**.
2. OMG UNITS. This isn't math, your answer is nothing without units. You can haz units! you must haz units. I can't emphasize this enough.
3. **Significant figures** are a thing. You should report your answer with appropriate number of significant figures (usually the number of significant figures you are given for the problem).
4. The expectation for this problem set is that you clearly demonstrate what you are calculating and why, and clearly outline the steps and process for solving the problem. The focus is on problem-solving skills, not getting the right numerical answer, and the clearer your work is, the easier it is to assign partial credit. You are expected to outline the problem (sometimes a diagram helps), present your strategy for solving it (including relevant equations, values, etc.), and solve it.
5. Finally, a **"reality check"** on your numerical answer is expected (does this answer make sense? Why or why not?).
6. Collaboration on problems is allowed (even encouraged!), but the final written work must be your own. ***A friendly reminder: Prof. Battersby has a zero-tolerance policy on cheating, including posting or looking up answers online, seeking or using previous solutions, copying, etc. Please just don't do it.***

Problem Set #2

Due: Monday February 13, 2023 at 12:30pm.

Reminder: Problem Sets will be spot-graded, including points for overall completeness.
Coding Problems: 3 problems for 22 pts total

Written Problems: 4 problems for 24 pts total

1. **(10 pts) Distance to and Mass of our Galaxy's SuperMassive Black Hole (SMBH).** Imagine that you have used an 8-m telescope to observe stars toward our Galaxy's Center (GC) regularly for more than 20 years. You happen to notice that one star moves back and forth across the sky in a straight line as it orbits the SMBH. This means that its orbit is directly edge-on. We are also seeing the longest extent of the orbit, meaning that when it appears to be farthest from the SMBH, it is indeed at its farthest point in all 3 dimensions (apocenter), and when it appears to be closest to the SMBH, it is in all 3 dimensions (pericenter). You measure the following properties of the star's orbit:

   - The extent of the orbit, s, is: s = $0.248''$
   - The period of the orbit (P) is: P = 15.24 years
   - The absolute value of the radial velocity of the orbit is: v_{peri} = 7326 km s^{-1} at pericenter and v_{apo} = 473 km s^{-1} at apocenter.

   Please answer the following questions and **be sure to include a reality check for your answers.**

   (a) What is the eccentricity (e) of the star's orbit?
   (b) What is the semi-major axis (a) in AU of the orbit?
   (c) What is the mass of the black hole (M_{BH}) in solar masses $M_\odot$?
   (d) What is the distance to the Galactic Center in kpc?

2. **(4 pts) Stegosaurus Stomp.**

   (a) Estimate the approximate number of times that the Sun has circled the center of our Galaxy since our Sun's formation.
   (b) Where in the Galaxy was the Sun when the dinosaurs died off? Report your answer in phase angle (in units of degrees), where the angle is measured relative to the Galactic Center. Our current phase angle is 0°, and if we moved clockwise 1/4 of the way around the Galaxy, our phase angle would be 90°, on the complete opposite side of the Galaxy would be 180°, and so on.

3. **(2 pts) Just take the M5.** The globular cluster M5 has an overall apparent visual magnitude of m_V = +5.95. Its overall absolute magnitude is M_V = -9.92. It is located about 7.5 kpc from Earth and is about 6.1 kpc above the Galactic midplane.

   (a) Estimate the amount of interstellar extinction between M5 and the Earth.
   (b) What is the amount of interstellar extinction per kpc?

4. **(8 pts) It's a Brick. In space.** Red Clump (RC) giant stars are good standard candles since they have a small luminosity (an absolute magnitude of about $_{Ks}$ = -1.60 mag, corrected for population synthesis modeling and translated from K to Ks) and color spread (an intrinsic (H-Ks) color of 0.07), trace the stellar density of the Galaxy quite well, and are easy to identify in a color magnitude

diagram (they are highlighted in Figure 1 below). These stars were observed toward an extremely dense molecular cloud in the center of the Galaxy, called "the Brick" (or G0.253+0.012) and analyzed in Longmore et al. 2012, ApJ, 746, 117L. The apparent magnitude and color where the RC stars diminish (farther away / redder stars are blocked by the cloud) are used to determine the extinction and distance toward the Brick. Figure 1 (and the caption) describes the data in more detail. Using these data and the following relevant information:

- The extinction law power-law α for the Galactic Center is about $\alpha = 2.21$
- The central wavelengths of the H and Ks bands are 1.677 μm and 2.168μm, respectively.
- In this wavelength range, the extinction can be approximated as a power-law of the form $A_\lambda \propto \lambda^{-\alpha}$

Please complete the following tasks.

(a) Determine the color / reddening at the location of the Brick and the apparent magnitude of the RCs in Figure 2.

(b) Determine the Ks band extinction (A_{Ks}) on the path to the Brick.

(c) Using these values, determine the distance to the Brick in kpc.

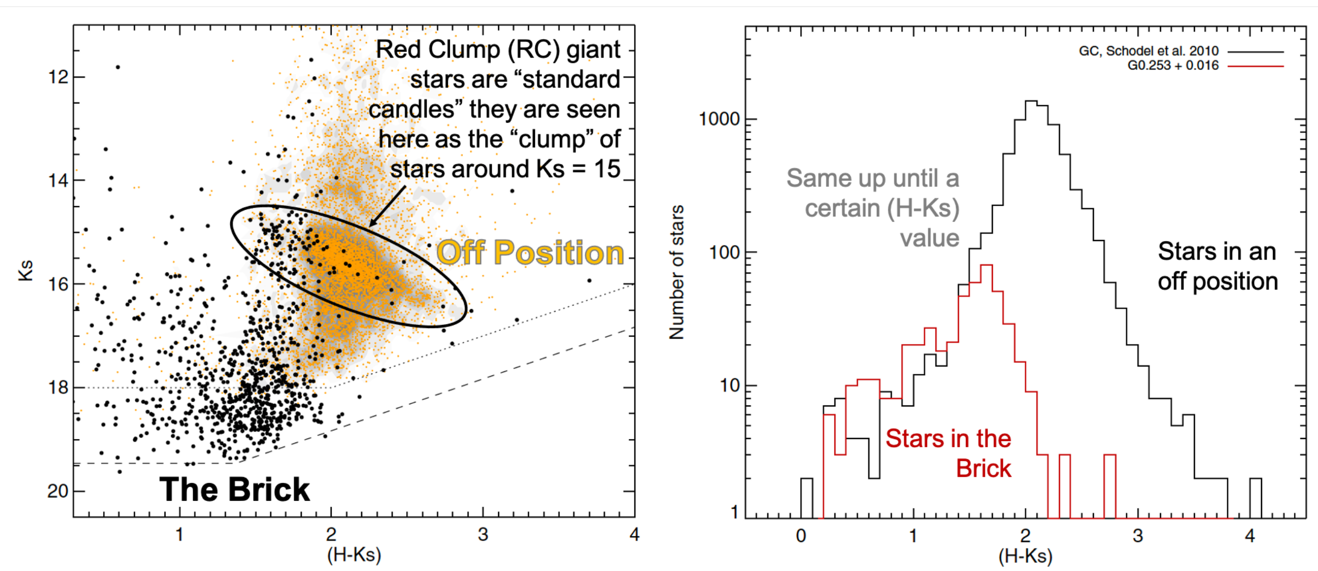

Figure 1: *Left*: Color Magnitude Diagrams from Longmore et al. (2012), comparing the apparent Ks-band magnitude on the y-axis and the (H-Ks) color on the x-axis. This plot shows stars on sightlines toward the Galactic Center and the source data is from the VLT/NACO (Schödel et al. 2010). This plot shows stars toward the cold, dense molecular cloud in the Galactic Center known as 'the Brick' in black, and toward an off position in orange and gray. *Right:* This plot compares the number of stars in each (H-Ks) bin for the Brick (red) and the off position (black) for the data from VLT/NACO, shown on the left.