Fall 2021 Final Exam
Due Dec 16 by 3 pm

PART 1: GAIA Data – Changing our Understanding of Stellar Evolution

GAIA is an European Space Agency satellite targeting over 1 billion stars from every every part of the Milky Way Galaxy, Over the course of the mission, GAIA will observe each target 70 times. From these measurements, we are obtaining positions, parallaxes and photometric information for each target. In addition, it will obtain low resolution spectroscopy for stars down to magnitude 19. This will provide the very first comprehensive sample of our Galaxy. The resulting data set will produce the largest most precise three dimensional map of the local Milky Way.

PART 1: Accessing the Data Table

GAIA recently published its 3rd data release. It is important to note that the data in this release is not complete. GAIA is continuing to observe, and the observations will continue to improve. For now, we will use the exisiting GAIA data to search for potentially interesting white dwarfs. To access the existing data we will need:

1. TopCat: TopCat is a Tool for Operating on Catalogs and Tables. It is invaluable when you are working with large data sets. Download and installation instructions can be found at http://www.star.bris.ac.uk/~mbt/topcat/
2. Once you have successfully downloaded and installed TopCat, you will need the GAIA data. TopCat uses Table Access Protocol to access data bases.
    1. In TopCat, click on VO → Table Access Protocol (TAP) Query. A window should pop up that shows all the astronomical services that allow TAP queries. Scroll through the list to get a feel for the amount of data services that are available.
    2. We want to find the GAIA data base, so type “gaia” as a keyword and hit return. This will return a list of many possibilities. Select the option ARI-Gaia. Click on the small icon at the beginning of the selection to list all the available possibilities.
    3. We want the GAIA source catalog from Data Release 3. Scroll down the list until you can locate gaiaedr3.gaia_source. Select that option.
    4. The URL should appear in the “TAP URL” window at the bottom of the TAP Query window. Once this happens, select “Use Service”.
    5. Now we need to select the specific catalog we want to access. Use the scroll bar in the left window to scroll through the possible selections. When you find gaiaedr3_gaia_source, click on it.
    6. Now a brief description (Name, Tables) should appear in the main TAP Query Window.
    7. Click on the “Table” Tab in the TAP Query window. A more detailed description of the table will appear. Read through it to familiarize yourself with the table.
    8. Click on the “Columns” Tab in the main TAP Query Window. A list of columns contained in the table will appear. There are quite a few, but we will only be accessing a subset of columns. Peruse the columns to see what is available. We will be accessing the following:
        1. Source_id – this is a very long telephone number for each object in the GAIA catalog.
        2. Ra, dec – these are the coordinates of the stars in the GAIA catalog.
        3. Parallax – this is an indication of distance. The larger the parallax, the closer the object is to us.

4. Gaia is obtaining photometric (or brightness) observations in 3 different bandpasses (or filters). You can find information about the bandpasses at https://www.cosmos.esa.int/web/gaia/iow_20180316. Different bandpasses measure brightness in different wavelengths of light . This is important to determine physical properties such as temperature. We will want to access to the following photometric parameters:
   1. phot_g_mean_mag, phot_g_mean_flux, and phot_g_mean_flux_error – these parameters are indicators of brightness in the "g" (general broadband) filter bandpass
   2. phot_rp_mean_mag, phot_rp_mean_flux, phot_rp_mean_flux_error - these parameters are indicators of brightness in the "rp" (red) filter bandpass. If the target is bright, the error should be small. However, if the target is variable, the mean flux will not be the same for each individual measurement, and so the error could be larger than expected. This will be important for identifying candidate pulsating white dwarfs.
   3. phot_bp_mean_mag, phot_bp_mean_flux, phot_bp_mean_flux_error – these parameters are indicators of brightness in the "bp" (blue) filter. If the target is bright, the error should be small. However, if the target is variable, the mean flux will not be the same for each individual measurement, and so the error could be larger than expected. Again, important for identifying candidate pulsating white dwarfs.
   4. bp_rp, bp_g – these two parameters measure the difference between the red and blue bandpasses (bp_rp), and general and blue bandpasses (bp_g). These parameters are important for determining temperature. For example, hot objects will have more blue photons than red, so bp_rp will be negative (remember the weirdness of the magnitude system – a brighter object has a smaller magnitude).
5. We will also want to access parameters concerning the noise properties of the photometric parameters.
   1. phot_rp_mean_flux_over_error, phot_bp_mean_flux_over_error, and phot_g_mean_flux_over_error each give a "signal to noise" estimate for the photometric measurements. We will be using these parameters to calculate a weighted error for each bandpass
      1. phot_bp_mean_flux_error/SQRT(phot_bp_mean_flux/(phot_bp_n_obs-1)) as bperr,
      2. phot_g_mean_flux_over_error/SQRT(phot_g_mean_flux/(phot_g_n_obs-1)) as gerr
      3. Here we have weighted each error by the number of observations obtained in each bandpass.

We will want to determine an estimate of the absolute magnitude (mg) of each object. We will determine these values using the parallax parameter, the apparent magnitude, and a little bit of calculation.

2. phot_g_mean_mag+5*log10(parallax/1000) as mg : This is the calculation that turns parallax into an absolute magnitude measurement.
   1. phot_g_mean_mag is the apparent magnitude measured by GAIA
   2. parallax is the measured parallax. It is divided by 1000 to convert to the correct units (convert from milliarcseconds to arcseconds).
3. The absolute magnitude is the magnitude the object would have if it were placed at a standard distance of 10 parsecs. The parameter mg is not measured directly by GAIA, but is calculated from available parameters when the data is downloaded. Mg is the label the column will be given in our output table.

3. We are now ready to access the data base and extract what we need for our investigation. Rather than expecting you to learn everything about Table Access Protocol, I provide the following example:
    1. SELECT source_id, ra, dec, parallax, phot_g_mean_mag,
       phot_g_mean_flux, phot_g_mean_flux_error, phot_rp_mean_mag,
       phot_rp_mean_flux,
       phot_rp_mean_flux_error, phot_g_mean_flux_error, phot_bp_mean_mag,
       phot_bp_mean_flux, phot_bp_mean_flux_error,
       bp_rp, bp_g, phot_g_mean_mag+5*log10(parallax/1000) as mg,
       phot_rp_mean_flux_over_error, phot_bp_mean_flux_over_error,
       phot_g_mean_flux_over_error, phot_bp_n_obs, phot_rp_n_obs, phot_g_n_obs,
       phot_bp_mean_flux_error/SQRT(phot_bp_mean_flux*phot_bp_n_obs) as bperr,
       phot_g_mean_flux_over_error/SQRT(phot_g_mean_flux/(phot_g_n_obs-1)) as gerr,
       pmra, pmdec, pmra_error, pmdec_error
       FROM gaiaedr3.gaia_source
       WHERE parallax > 5
       AND parallax_over_error > 9
       AND phot_bp_mean_flux_over_error > 10
       AND bp_rp > -1.5
       AND bp_rp < 2.9
       AND phot_g_mean_mag+5*log10(parallax/1000) > -8.0
       AND phot_g_mean_mag+5*log10(parallax/1000) < 11.5

    2. This script first outlines what parameters we want to extract (SELECT), then the catalog to use (FROM) and then gives a range of values to use for screening objects (WHERE). For example, this query will only select objects with parallax measurements greater than 5. Also, phot_bp_mean_flux_over_error must be greater than 10, and the bp_rp (color/temperature parameter) must be between -1.5 and 2.9.
4. The lower portion of the TAP Query window is devoted to submitting specific queries.
    1. First, change the Max Rows from 100000 (default) to 1000000 (max).
    2. Next, copy the above script and paste it into the ADQL Text window. Make sure you have copied the entire script, and not left out anything.
    3. Click on “Run Query”.
    4. A new “Load New Table” window should appear. It will tell you the progress of your query. It may take some time to complete the query.
5. When the query is finished, go back to the main TopCat window. The Table list should now include a table. A description of the table should be given in “Current Table Properties”.
    1. The table is in FITs format. FITS stands for Flexible Image Transport System. This means the table consists of a small text header, and a binary table. Because it is a binary table, you cannot read the table directly.

6. Look at the contents of the table. To do this, click on Views –> Table Data in the main TopCat window. The Table Browser is a spreadsheet window containing the table data. The table is quite large, with over 1.5 million lines and a column for every parameter we extracted.

PART 2: Identifying the White Dwarf Stars

Our goal is to use the GAIA data to search for interesting white dwarf stars for future study. To do so, it would be helpful to be able to visualize the GAIA data and isolate the white dwarfs.

Lets start off with a simple plot of our data.

1. In Topcat, click on "Graphics" → "Plane Plot". A new window should appear with a strange looking plot. Topcat by default uses the first two columns of the table to create the plot. In this case, the first two columns are the source identifier and the right ascension. These are not very interesting parameters to plot, so we need to change the parameters.
    1. In the Plane Plot window, click on the downward arrow to the right of the X box currently listing source_id as a parameter. A list of all the columns in the table will appear. Scroll down and click on bp_rp. This is a very important physical parameter (brightness in blue – brightness in red) that gives an indication of temperature of the object.
    2. Now we need to select total brightness for the Y axis. Click on the downward arrow to the right of the Y box currently listing ra as its parameter. Scroll down and click on mg. You now have a plot that shows the distribution of temperatures of objects as a function of absolute magnitude. Absolute magnitude is the brightness an object would have if you could place it at a standard distance of 10 parsecs (about 30 light years). Absolute magnitude is therefore a good indicator of how much total energy an object is emitting.
    3. Astronomy can be very particular about how things are plotted. We like to have more hotter, more luminous objects in the upper left, and less luminous, cooler objects in the lower right. Remember, larger values for magnitude mean fainter objects. Therefore, hot, bright objects will have a negative value of bp_rp. To have hot objects in the upper left, we need to flip the direction values are plotted on the y axis. Click on "Axes" in the lower left subwindow of the Plane Plot window. Then click "Y Flip:". Now the more luminous, high temperature objects (with low absolute magnitudes and negative bp_rp values) are in the upper left, and less luminous, cooler objects (with higher absolute magnitudes) are in the lower right.
    4. You now have a plot known as a Herzsprung-Russell(HR) diagram. Remember that each point in this plot represents an astronomical object. There are stars of all masses, ages, and types included in this plot. This is an amazing plot!
        1. Go here https://sci.esa.int/web/gaia/-/60198-gaia-hertzsprung-russell-diagram to learn more about the GAIA HR diagram.
        2. Save a copy of your HR diagram, and label its parts to include in your final report.
        3. Explain in a few sentences what each part is.
        4. What are some differences you see between your plot and the plot in this article?
        5. How do you think these differences are explained?
        6. Include this discussion in your final exam report.

2. We are interested in the white dwarfs. How do we isolate these stars for closer study? We need to identify a parameter that is unique to white dwarfs.
    1. Most of the white dwarfs occupy the "white dwarf cooling track", which is represented by the lower diagonal "streak" of stars going from the left to lower right of your graph. We would like to isolate this section of the plot.
    2. Click on "Axes" in the lower left subwindow of the Plane Plot window.
    3. Click on the "Range" tab. This should give you a window where you can enter values for the ranges of x and y.
    4. For the x range, enter -0.7 for the minimum and 1.3 for the maximum
    5. For the y range, enter 3.8 for the minimum, and 10.0 for the maximum (remember we flipped the y axis).
    6. Click "Submit"
3. This gives us a better view of the white dwarf cooling track. In very broad brush strokes, a white dwarf is a "dead star". Most stars like the sun will form white dwarfs at the end of their lives. White dwarfs are remarkably similar in mass. Also, white dwarfs have no internal energy source, so once they are formed, they gradually cool by radiating their residual thermal energy. Our plot shows young, hot white dwarfs at the top (upper left) of the white dwarf cooling track, and cooler, older white dwarfs as the track proceeds to the lower right. If we could watch a single white dwarf over time, it would start at the upper part of the white dwarf cooling track and migrate downward as it ages.
4. We can reveal further interesting features by weighting the points ad changing a few parameters.
    1. Click on the table name in the lower left subwindow of the Plane Plot window. In the right subwindow, there should be three tabs: Position, Subsets, and Form. Click on Form.
    2. In the right portion of the lower subwindow, there should now be sections for Shading, Global Style, and Subset Styles. In Shading, click on the downward arrow next to Mode, and select "Weighted". Now we need to select the parameter to weight each point by. Click the downward arrow next to the "Weight" box and select phot_g_mean_flux_over_error. The plot should change color, and there should be a vertical color bar showing how colors are distributed with values of our weighting parameter.
    3. Change the "combine" parameter to "sum".
    4. Now your graph should look very yellow. We need to select a different color scheme.
        1. In the left portion of the subwindow, click on "Aux Axis".
        2. TopCat has many built in color schemes that we can use. In the right portion of the subwindow, you can experiment by using the left and right arrows on the Aux Shader box to scroll through the various color schemes. After you've looked through them, select "HotCold".
        3. This is still a little too much of one color, indicating that our scaling is not ideal. The default scaling for the weights is "linear". This means that the range of the weighting parameter is calculated and color is assigned in a linear fashion from the highest to the lowest values. This is not always the best way to do things when you have a large dynamic range. Change the default scaling to "log". This allows you to squeeze a larger dynamic range into the color scale. Now we are starting to see some structure.
5. This plot shows should be yellow, red, and orange. It shows quite a bit of structure in the white dwarf cooling track.

1. A recent discovery from GAIA is the "splitting" of the white dwarf cooling track near bp_rp=-0.03 and mg = 7.0 We are still working on the exact reason for this, but it is believed to be due to the presence of hydrogen in some white dwarf atmospheres.
2. Another new discovery from GAIA is the faint tail that seems to cross the diagram around mg = 8 and joins with the white dwarf cooling track around bp-rp=0.4, This tail may be responsible for the thicker appearance of the white dwarf cooling track around this area.

6. For this project, our goal is to use GAIA data to search for new white dwarf pulsators. Why are pulsations interesting? Well, we can use the frequencies that a star pulsates at to build a model of the interior of the star, much as scientists use earthquakes and the propagation of seismic waves to measure the interior of the earth. It is one of the best ways to have to really "see" what is going on inside of stars.
   1. The most numerous class of pulsating white dwarfs are found near where the white dwarf cooling track splits near bp_rp =-0.03.
   2. You might notice a subtle blob of points with lighter colors near bp_rp =0. Lets review what the colors mean. We are using the parameter "phot_g_mean_flux_over_error" as a weight to assign point color. This parameter is takes the mean brightness of all of GAIA's measurements of the star and divides by the associated error. If the error is small, this parameter will be fairly small (red or orange in our color scheme). If the error is large, this parameter will be much larger (yellow or blue). Now, "bad data" can give large errors. But, stars that are pulsating, or varying their brightness over time, will also have large errors associated with their GAIA measurements, simply because GAIA does not measure the same brightness in every measurement. This is the case here. This blob of points represents the most numerous class of white dwarf stars that are known to pulsate.
7. Lets zoom in on these white dwarfs.
   1. For the x range, enter -0.2 and 0.08. For the y range, enter 6.5 and 7.23. Click Submit.
   2. Now we have a plot of teeny tiny points. We might want to make these larger. Click on the

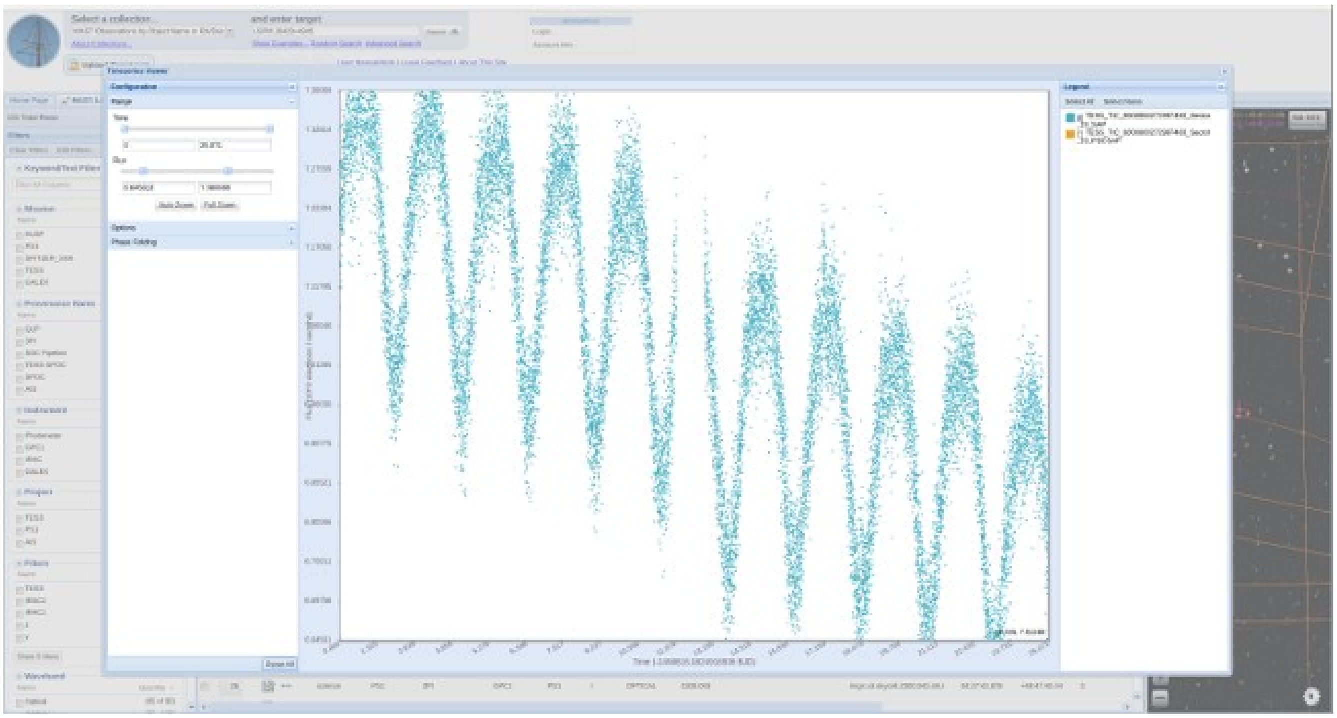
Part 3: Investigating Individual white dwarfs

1. The question we are looking to answer: What exactly are these objects and how do they fit into our understanding of white dwarf evolution.
2. The plot is tied to the table we opened earlier. Click on one of the blue or yellow points near the center of the plot. If you now go back to the table window, a row should be highlighted that corresponds to the point you clicked on.
3. Now we are ready to find out exactly what this object is. Your results for this section will be entered into a shared Google spreadsheet.
4. There is an astronomical website called Simbad that has merged the GAIA data base with its older catalogs. Open an internet browser and go to http://simbad.u-strasbg.fr/simbad/. This early DR3 data release is not yet directly available in Simbad, so we will have to search by coordinates. Click on "coordinate query".
   1. Enter the ra and dec for your object into the search field. The ra must be first, followed by the dec. Make absolutely sure you copied both coordinates correctly. Once you are satisfied, click "Submit query" in the Simbad window.
   2. Simbad should return a short list of objects within 2 arcminutes those coordinates.
      1. Select the object with the "Otype" of WD (WD stands for white dwarf).
      2. If there is no WD, select the object closest to the coordinates you entered. This will be the object with the smallest value in the dist(asec) column.
      3. If no objects are found near your coordinates – this object is "not found" and you will record this in the following steps.

3. Known sources will be easy. Record the following information you find from the GAIA table and on Simbad in the project spreadsheet:
    1. GAIA DR3 source_id
    2. the target name and star type from Simbad
    3. the right ascension and declination from GAIA (both in degrees)
    4. the phot_g_mean_magnitude from GAIA
    5. bp_rp from GAIA
    6. the parallax from GAIA
    7. the proper motion in the x and y directions from GAIA. (Proper motion is the measured velocity of the star across the sky).

4. To finish filling out rest of the spreadsheet , we need to do a bit of investigation. In the Simbad Window, there is a button/tab labeled "AladinLite". Clicking on this gives you a view of the sky around the object's coordinates. The red cross should land close to the target star.
    1. GAIA data is not yet good enough to separate the fluxes of close stars. We need to determine if the object could be a binary star .
    2. AladinLite allows you to look at the sky as shown by different surveys at different wavelengths (the list to the left of the AladinLite window). The best one for our purposes is DSS2 (Digital Sky Survey 2).
    3. Most binary stars contain a red (cool) and a blue (hot) component. If the object is possibly binary, you may see an image where one side of the star is blue, and the other is red.
    4. If the object is not clearly a binary, it might be helpful to switch between DSS2/blue and DSS2/red. If the star is a member of a very close binary that contains stars of different temperatures, the red component will appear in the DSS2/red image, and the blue component will appear in the DSS2/blue image. When you switch back and forth, the target object will appear to move a bit, while the other stars in the field stay stationary.
    5. You can also zoom in and out using the +/- buttons on the right side of the image.
    6. Make a note in the Binary column in the spreadsheet if this object seems to be a binary star.
5. We would also like to know if any additional information is available about the physical properties of this object. Properties include mass (or log g, the logarithm of the surface gravity), effective temperature (the surface temperature), magnetic fields, or the presence of any metals in the star's atmosphere. Scroll through the Simbad page until you find the References section. Click on "Display". Pick 2 of the available references (titles that mention physical properties, catalogs, or surveys are your best bet) and look through them. You don't have to read the articles in detail. Look for tables that contain information on stellar properties, or find where your object is mentioned. Add any information you find to the shared spreadsheet.
6. As a final step, we would like to know if this star has been observed by TESS. TESS is a satellite that is looking for planets around other stars. It does this by finding transiting planets. A byproduct of TESS is lots of observations of the brightness of lots of stars. We may be able to find if our candidates exhibit brightness variability by using the TESS observations.
    1. Go to this web page: https://mast.stsci.edu/portal/Mashup/Clients/Mast/Portal.html
    2. At the very top of the page, enter the RA and Dec of your target in the "and enter target:" window. Then click on "Search"

3. If the results of the search contain entries from the Mission “TESS”, then this object has been observed by TESS. Enter “Yes” in the Tess box in the shared spread sheet.
    1. There should be several entries marked by an icon containing a bent red line. These are photometry observations. Click on these icons and look at the plotted light curve. If the star is variable, you should see changes in the brightness (see example below). Significant gaps in the observations don’t count. This is where the spacecraft stopped observing to download data. Based on your evaluation, enter “yes”, “no” or “maybe” in the variable column in the shared spreadsheet.
    2. Take a screen shot of your suspected variables and include it in your final exam. Make sure to identify the star.



Example of a TESS light curve showing variability.

7. Everyone should select 10 points from along the white dwarf tail in the Plane Plot for investigation. I have created a Google spreadsheet for recording the results. The spreadsheet has been shared with everyone. Try not to duplicate objects.

PART 2: Color Images

An important goal of this class is to become familiar with astronomical imaging techniques. From the class website, download the Trifid Nebula data set (taken with the 1 meter SARA telescope in the Canary Islands. Using the techniques you have learned from the computer work, create a color image of the nebula. Record your steps. Send your image and your steps to me at jlp@udel.edu.

What to turn in:

Your final report that you hand in to me should include the following:
1) A copy of your GAIA HR diagram and your zoom-in of the white dwarf “tail”.
2) Answers to the questions in this part of the final
3) Screen shots of TESS light curves of suspected variables.
4) Your color picture of the Triffid Nebula and the steps you used to create it.

I will also see your results in the spreadsheet.