Queensland University of Technology

QUT Astrophysics Research Group
AstroLab C3:
Hertzsprung-Russell Diagram

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Queensland University of Technology — Semester 2, 2022

Name and Student Number: _____

Date: _____

Group Members: _____

Introduction

AstroLab C3 centres on a computer-based activity where you download and process data collected by the European Space Agency's Gaia Space Observatory to plot your own Hertzsprung-Russell diagram (aka H-R diagram), which is an important tool in the study of stellar evolution.

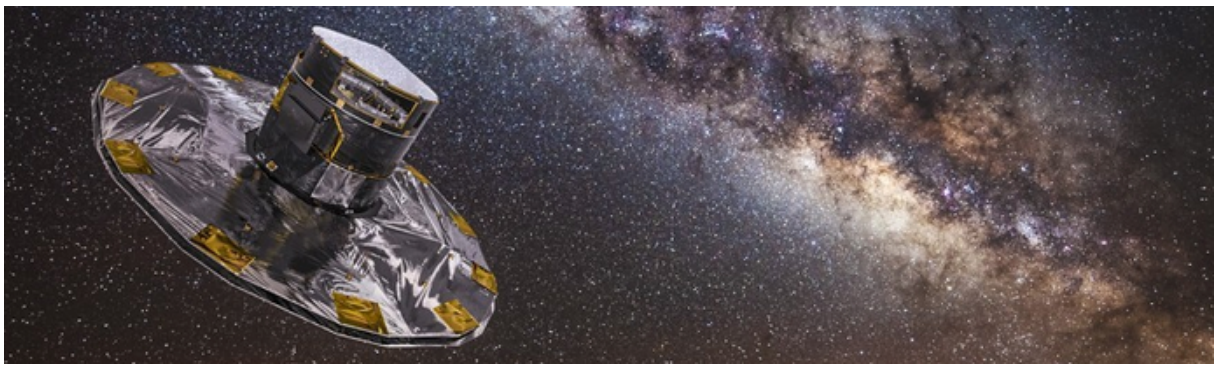

Figure 1: An artist's concept of the Gaia spacecraft. Credit: ESA.

Shown in Figure 1, Gaia, the Global Astrometric Interferometer for Astrophysics, was launched in 2013 with the goal to create the largest, most precise three-dimensional map of the Milky Way by surveying about 1% of the galaxy's 100 billion stars. Thanks to the data Gaia has collected, we're able to produce H-R diagrams. The H-R diagram originated in 1911 when the Danish astronomer, Ejnar Hertzsprung, plotted the absolute magnitude of stars against their colour (or effective temperature). Independently, in 1913, the American astronomer Henry Norris Russell plotted spectral class against absolute magnitude. The result, a H-R diagram, showed us that the relationship between temperature and luminosity of a star was not random but instead appeared to fall into distinct groups. You will produce your H-R diagram in this activity to investigate these groupings.

Software

For this activity, all you require is the free software, TOPCAT (Tool for OPerations on Catalogues And Tables), which is an interactive graphical viewer and editor for tabular data. Its aim is to provide most of the facilities that astronomers need for analysis and manipulation of source catalogues and other tables. It understands a number of different astronomically important formats (including FITS, VOTable and CDF) and more formats can be added. It is especially good at interactive exploration of large (multi-million row, lots of columns) tables.

Worksheet Entry 1

Question: What does the file format “FITS" stand for and how is it used in astronomy?

TOPCAT a stand-alone application which works quite happily with no network connection. However, because it uses Virtual Observatory (VO) standards, it can cooperate smoothly with other tools, services and datasets in the VO world and beyond.

Worksheet Entry 2

Question: What is the Virtual Observatory (VO) and how does it assist astronomers in their day-to-day activities?

Installation

TOPCAT is written in the Java language, which means it can be run on a wide range of platforms, without requiring any recompilation - you just need to ensure that you have a suitable Java Runtime Environment (JRE). If you don’t have Java installed, or have an unsuitable version, you can obtain the Java SE for Linux, MacOS, MS Windows and Solaris from Oracle’s web site (you only need the "JRE" rather than the "JDK" download). For download options, please visit the official TOPCAT webpage. TOPCAT is also installed on most of the PCs in the QUT Physics Laboratories. Please see your demonstrator if you require assistance.

Procedure

This activity uses data from Gaia DR2 (Brown et al., 2018) to help you produce a H-R diagram. In this activity, we will use a Table Access Protocol (TAP) query to download all the nearby Gaia sources with good astrometry and photometry, and calculate their absolute magnitudes to construct a H-R diagram, performing a couple of cleaning operations to improve the data along the way. This example is based on a TOPCAT tutorial (Taylor, 2017) and loosely follows Appendix C of the Gaia DR2 astrometry paper by Lindegren et al. (2018).

Worksheet Entry 3

Question: What is meant by "good astrometry" and "good photometry" in the above?

Acquire data from TAP service

1. From TOPCAT, open the TAP window 
2. Search for “Gaia” and select one (preferably ‘ivo://esavo/gaia/tap’) and select `Use Service`. This may take some time to download.

3. Choose the mode `Asynchronous` (just above the ADQL text entry panel). This query may take a minute or two, so a synchronous query might time out (with the unhelpful result, probably, *"TAP response is not a VOTable*").

4. Execute the following query (if you cut and paste, be sure to adjust line breaks and spacing etc.):

```
SELECT ra, dec, parallax, phot_g_mean_mag, bp_rp,
        astrometric_excess_noise,
        phot_bp_rp_excess_factor
FROM gaiadr2.gaia_source
WHERE parallax > 10
        AND parallax_over_error > 10
        AND phot_bp_mean_flux_over_error > 10
        AND phot_rp_mean_flux_over_error > 10
```

   Give this a minute or two to load. You should get a table with 338,833 sources; they are nominally within 100 pc, and have ϖ (parallax), BP and RP (photometry) values with small errors.

Worksheet Entry 4

Question: The BP and RP values in your table relate to the photometry of the Gaia sources. What does BP and RP stand for and at what wavelength range do they operate? Hint.

Plot H-R Diagram

1. Click on the column metadata icon and add a new column calculating absolute G magnitude, using parallax:

   Name: `g_abs`
   Expression: `phot_g_mean_mag + 5*log10(parallax/100)`
   Units: `mag`

2. Click on the plotting window icon and change the X-axis to `bp_rp`, which is the BP-RP colour, and the Y-axis to `g_abs`, which is the absolute G magnitude.

3. Select the Axes control icon and within the `Coords tab`, select the `Y Flip` checkbox.

4. Play around with the different shading modes in the `Form` tab. You could try colouring the points using the other columns via the `Weighted` mode, as shown in Figure 2.

Worksheet Entry 5

Question: Along the X-axis, you've plotted the BP - RP colour. In this case, what does "colour" represent?.

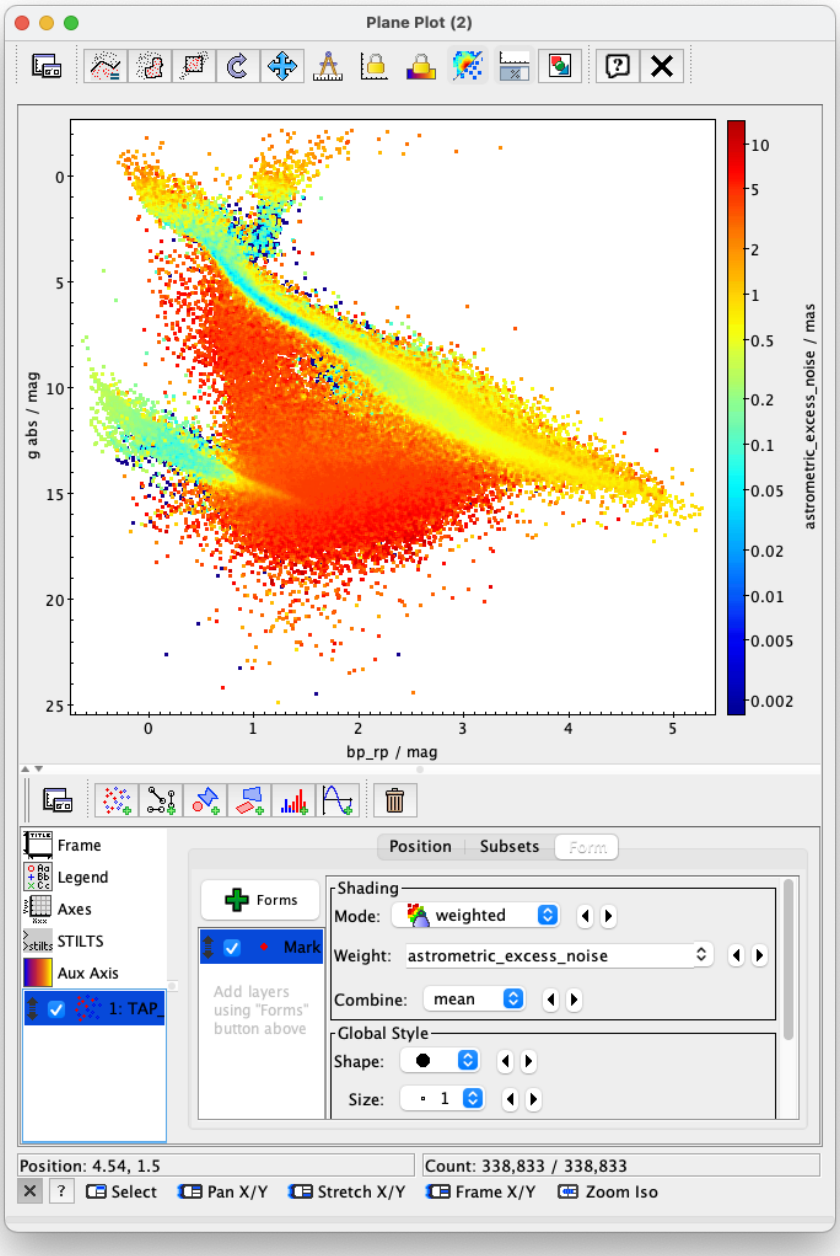

Figure 2: Example from TOPCAT

Exclude astrometrically poor sources

1. The aim here is to omit stars with poor astrometry. From the main TOPCAT window, click the Subset icon and define a new subset with the following details:

   Subset Name: `astrom_ok`
   Expression: `astrometric_excess_noise < 1`

2. Go back to your plot and in the `Subsets` tab, unselect `All` to ensure only your `astrom_ok` sources are plotted. There should be fewer spurious sources now.

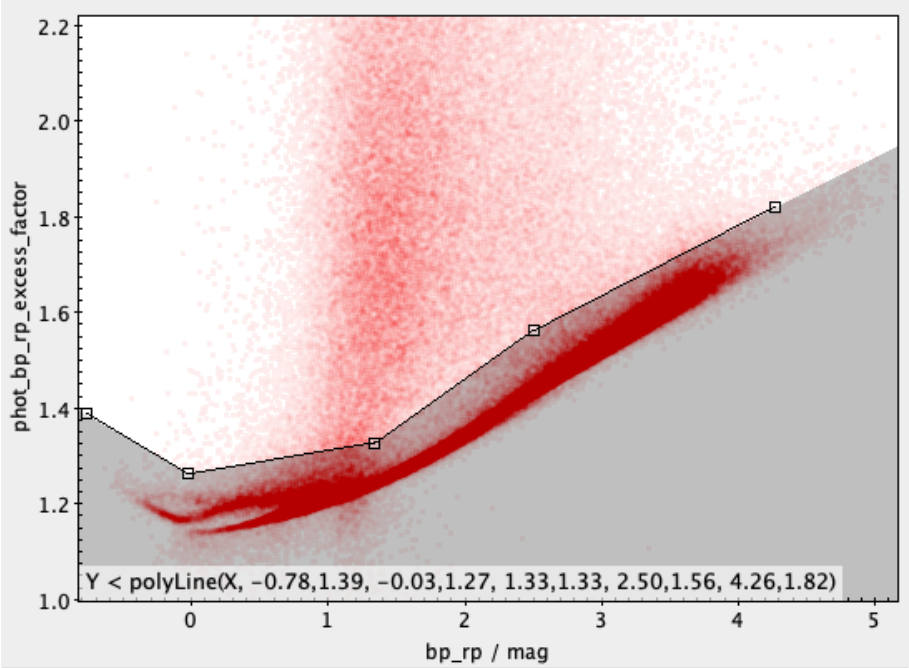

Figure 3: Polygon selection to remove poor photometric sources in TOPCAT

Exclude photometrically poor sources

1. From the main TOPCAT window, open a new plotting window with the X-axis as `bp_rp` and the Y-axis as `phot_bp_rp_excess_factor`. The quantity on the Y-axis is a measure of the photometric reliability. Here, high values are bad, but how high is also colour-dependent. We will define a region in this space to exclude unusually high values. This time, we will interactively draw a polygon to select these sources.
2. From the plot window, click on the define subsets icon.
3. Select `Below` from the dropdown box.
4. As shown in Figure 2, select a few points above the overdense region until the shaded area roughly covers it.
5. Once done, click on the define subset button again.
6. Enter a subset name (e.g. `photom_ok`) and select `OK`.
7. From the main TOPCAT window, click on the Subset icon to view the new subset along your previous subset, `astrom_ok`.

8. We want to combine these two subsets, so select a new subset  with the following details: **Subset Name**: `ok` **Expression**: `astrom_ok && photom_ok`. If done similar to me, you should have slightly more than 70% of sources using these flags.
9. Return to your HR diagram and ensure only the `ok` subset is selected. You should find your plot now contains fewer spurious sources.

Explore the HR Diagram

The photometry and astrometry in Gaia DR2 is so good that plotting a Herzsprung-Russell Diagram by following the steps above gives a lot of astrophysical information.

Worksheet Entry 6

Question: Print or save your plot and then label the different populations as (1) Main Sequence, (2) Giant Branch, (3) White Dwarf Sequence. You should write a paragraph or two with details of these populations and how the H-R diagram facilitates stellar astrophysics.

References

Brown A. G. A., et al., 2018, Astronomy and Astrophysics, 616, A1

Lindegren L., et al., 2018, Astronomy and Astrophysics, 616, A2

Taylor M., 2017, Informatics, 4, 18

Record your data and answer questions in the spaces provided. Be sure to hand your worksheet to a demonstrator before the end of the session.

1. **Question:** What does the file format “FITS" stand for and how is it used in astronomy?

2. **Question:** What is the Virtual Observatory (VO) and how does it assist astronomers with their day-to-day duties?

3. **Question:** What is meant by "good astrometry" and "good photometry" in the procedure?

4. **Question:** The BP and RP values in your table relate to the photometry of the Gaia sources. What does BP and RP stand for and at what wavelength range do they operate? Hint.

5. **Question:** Along the X-axis, you’ve plotted the BP - RP colour. In this case, what does “colour" represent?.

6. **Question:** Print or save your plot and then label the different populations as (1) Main Sequence, (2) Giant Branch, (3) White Dwarf Sequence. You should write a paragraph or two with details of these populations and how the H-R diagram facilitates stellar astrophysics.