Color-magnitude diagrams of open clusters

In this lab, you will answer these questions (and show plots to back up your answers):

1. Who was right about the distance to the Pleiades, astronomers using data from the Hipparcos mission, or everyone else? (Hipparcos measured a distance of 120 pc, at odds with previous estimates that all clustered around 133 pc – more at https://www.skyandtelescope.com/astronomy-news/resolving-pleiades-distance-problem-08282014/) Or maybe neither – what is your best estimate of the distance to the Pleiades, and its uncertainty, using Gaia data?

2. Which cluster is older, the Pleiades or M67? How can you tell?

3. Does either cluster have any red giants?

4. Does either cluster have any white dwarfs?

Background: Why a color-magnitude diagram?

The Hertzsprung-Russell diagram (HR diagram) is one of the fundamental tools of stellar astrophysics, allowing us to visualize the relationship between the key variables of effective temperature and luminosity for different kinds of stars, at different stages of evolution.

However, neither luminosity nor effective temperature is directly observable. To get luminosity, we need to make assumptions about the relationship between the brightness in the band(s) we observe and the energy output at (all) other wavelengths (called a bolometric correction). And effective temperature requires some calibration of a temperature-dependent observable, like spectral class or a color in some set of bandpasses. (Recall that color in astronomy has a specific technical meaning: a color is the difference of the magnitudes in two bandpasses, like $B - V$ or $J - K$).
Thus, instead of a $T_{\text{eff}}$ vs. $L$ plot (sometimes called the “theorist’s HR diagram”), in observational astronomy we often plot a similar diagram that is closer to the observables: a color-magnitude diagram. This has some photometric color on the x-axis, and some absolute magnitude on the y-axis. Plotting these temperature-like and luminosity-like quantities shows us the same overall patterns, without as many intervening assumptions between observations and plot.

In this lab, you will use a relatively new dataset (the second data release from the Gaia satellite) and an on-line portal for data visualization (Filtergraph) to examine the properties of two open clusters, the Pleiades and M 67. Along the way, you’ll learn more about data visualization and analysis with modern tools.

**Making a first plot using Filtergraph**

Filtergraph is an online portal that allows for easy and flexible visualization of large datasets, and it allows you (if you create a free account) to upload and store your own data. It interfaces well with astronomical data (partly since some astronomers had a hand in creating it), so it is well suited for our purposes.

Go to [https://filtergraph.com/](https://filtergraph.com/) and set up a free account¹ – this will allow you to easily save any plots you create and come back to them later.

Log into your new account, then go to [https://filtergraph.com/gaiadr2pleiades](https://filtergraph.com/gaiadr2pleiades)

This loads a dataset with Gaia DR2 data for the Pleiades cluster. Every “portal” in Filtergraph has a dataset associated with it, and a unique URL where you can access it. This is a portal I created by using Vizier (more about that shortly) to access the Gaia DR2 catalog, and select all sources that met these requirements:

- Projected location on the sky (RA and Dec) within 1.5° of the center of the Pleiades cluster. Note that this is a bit bigger than the obvious high-density region of stars on the sky you see with your eye. But there is no sharp edge, so this casts a relatively wide net for possible

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¹ This won’t sign you up for any spam email or anything like that; this is a non-profit / academic operation created by Vanderbilt University, not a commercial venture trying to sell you anything. [Here](https://filtergraph.com/terms) are the terms of use if you want to check.
members, and we’ll refine it later to select likely members in other ways.

- Measured parallax whose value is more than five times its own uncertainty, i.e. \( \frac{\text{parallax value}}{\text{parallax uncertainty}} > 5 \). This eliminates very faint sources with poor parallax measurements.

The default plot you get at first is just a graph of the first two quantities in the dataset plotted against each other:

In this case that is RA vs. uncertainty in RA, which is really uninteresting. Instead, use the drop-downs on the left to make some other plots with the provided quantities. For example, you could plot RA vs. Dec. to see the distribution of the sources on the sky. Play around with a few plots. A few things to note:
• If you click the green “more” label under the Z-axis slot on the left, you will have axis to more controls, like limiting the range of a given axis, or reversing it, or plotting on a log scale.

• If you click and drag on the plot, the plot will zoom in to that part of the data. You can reset the range with a button in the upper right.

• You can plot simple mathematical functions of the data, too – try plotting the square of one quantity vs. the ratio of two other quantities. (Not that that’s a meaningful combination, but just to get the hang of it.)

Aside: what are all these quantities in the dataset?

Some of the quantities available for plotting have obvious names (e.g. you can probably figure out that “RA_ICRS” is Right Ascension) but others aren’t very clear. What are they? To figure it out, let’s take a look at where the data came from. We’ll be using Vizier, which is an online database of a wide variety of astronomical catalogs. We won’t do much with it in this lab, but we’ll use it to get a sense of what these fields are.
In a new tab or browser window, go to \url{http://vizier.hia.nrc.ca/viz-bin/VizieR-3?-source=I/345/gaia2}, which is a search form for Gaia DR2. You’ll see an interface like the one shown above.

This is a form that you could use to search the catalog for additional sources. For our purposes, we’ll just use it to understand what we’re looking at in Filtergraph. Note that the labels to the left of each search box are the same labels you see in Filtergraph. To the right of each box, there are two things: a label immediately to the right telling you the units, followed by a longer text description of what the quantity is. So, e.g., we can verify that RA_ICRS is indeed right ascension, and that it is in units of degrees. Not all quantities shown here are included in the Filtergraph portal. The ones I uploaded are mostly the default set, which are the ones with the checkmark in the left-hand column.

Take a minute to look over what the various default quantities are. Then let’s go back to Filtergraph, but keep this window open so you can refer to it as you make other plots.

**Plotting a rough color-magnitude diagram (CMD)**

Now that you know what the quantities are, let’s plot a color-magnitude diagram. Pick one color for the x axis, and one magnitude for the y axis, and plot them. There are a few to choose from, but just pick one set and try it. For now, just plot apparent magnitude. (Why is this OK for a cluster?) Try to get it to look as much like a textbook color-magnitude diagram as possible, setting axis ranges to trim out regions where there aren’t very many points.

You should be able to get something that looks *mostly* like an HR diagram, with some indication of a main sequence, but with a lot of other junk as well. That “junk” is from stars that aren’t members of the cluster, so our next step is to get rid of them.

**Cleaning up the CMD**

*(For this part, you may want to leave your current CMD open in one tab or window, and do this exploration in a different tab or window – it’s fine to have multiple views of the same portal open at the same time.)*
Filtering on proper motion

One way to find members of the cluster is to look at proper motion. All members of a cluster should be moving together through space, and that space motion is often different from that of typical background or foreground stars. The background stars in particular should mostly have motions that cluster around zero (they are far away on average), so what we’re looking for in the plot is an overdensity of stars at some non-zero proper motion.

Make a plot of RA proper motion vs. Dec. proper motion, and use it to identify the cluster. Zoom in as needed so you can see what’s going on with the data – things may not be obvious at the default zoom range.

Once you have located the clump of stars in proper motion space that you think represents the cluster, note down the range of values that includes that clump but excludes other stars.

Now go back to your color-magnitude diagram, and we will filter the data to only include stars in that proper motion range. In the upper left, click the green box that says “Filter the data”, and enter the range of values you found above. If you have identified the cluster correctly, your diagram should clean up considerably!

Filtering on distance

Now that we have a good-looking CMD, we should be able to get a good idea of distance to the cluster, and use that as an additional filter.

There are a couple of possible ways to do this:

- Set the color of the points to be related to the distance, and look for outlying points. You may want to progressively refine your filter, since the color scale will change to match the remaining range of the data, allowing you to see smaller changes as you iterate.

- Make a separate histogram plot of distance and look for a peak. If you do this, make sure that your other filters (e.g. on proper motion) are applied as well.
Finalizing your Pleiades CMD

Once you have cleaned up your CMD as much as possible, do a few more things to improve it for presentation:

- Change the labels of the plot axes, and the plot title, to make them more understandable.

- Change the y axis to plot \textit{absolute} magnitude rather than apparent magnitude. (Remember that Filtergraph can apply mathematical functions to your data! Think here about what you need. Note that \textit{log} represents natural log here; you need \textit{log10} to get the base-10 logarithm.)

- Optionally, use the size of the points and/or change the color scheme to convey additional interesting information about the cluster.

- Optionally (if you have time and want an additional challenge): you may still have a cloud of points at the faint end that don't really lie on the main sequence and don't really seem likely to be cluster members, but which haven't (yet) been removed by any of your filters. Can you find other criteria that would help you clean up some of these points? A couple of things you might try are using the lasso tool (see upper right of the plot interface) to highlight those points, and then seeing where they appear in other plots; and in particular, looking at color-color plots (i.e. two different photometric colors plotted against each other) rather than color-magnitude plots to see if that gives any additional insight.

Once you have your diagram looking good, do two things:

1. Click “Add to notebook” to save the current view of the portal if you want to come back to it later.

2. Click “Save” to save a copy of your plot as a PNG.

Another cluster: M67

Now that you understand how to use Filtergraph to explore data, apply the same approach to the cluster M67. You can find the M67 Gaia DR2 data
(selected in much the same way at the Pleiades data) at
https://filtergraph.com/gaiadr2m67.

Produce the best-looking CMD you can for M67, using the same axes you
used for your Pleiades plot. Save the plot in a notebook in Filtergraph, and
save a PNG copy as well.

To turn in:

- Your best Pleiades and M67 color-magnitude diagrams.
- Answers to the questions posed at the beginning of the lab. In each
case, use plots saved from Filtergraph as needed in order to explain
how you arrived at your conclusions.