

ISP205L, Week 13

Computer Lab Activity

The Distance to the Pleiades

1. The Pleiades Star Cluster as a Part of Our Galaxy.

In the previous lab exercise, you hopefully deduced that the Pleiades star cluster was formed rather recently. Clusters of young stars like this are found in or near the disk of our Galaxy, because the stars formed from the gas which is concentrated in that disk. But where in the disk does the Pleiades cluster lie? Our Sun is located about 8000 pc from the Galaxy's center. How close or far is the Pleiades in comparison to that distance?

2. The Distance to the Pleiades

During this week's lab exercise, you will measure the distance to the Pleiades by using a simulated telescope to measure the apparent brightness (or "flux", which we will designate as F) of various stars in the cluster, and then comparing that to the known intrinsic brightness (or "luminosity", designated here by L) of the same stars. Recall that the *luminosity* is the total energy per unit time emitted in all directions by the star, while the *flux* is the energy per unit time per unit surface area that reaches an observer at a distance d from the star. The relation between flux and luminosity is

$$F = \frac{L}{4\pi d^2} \quad (1)$$

This can be solved for d , to find

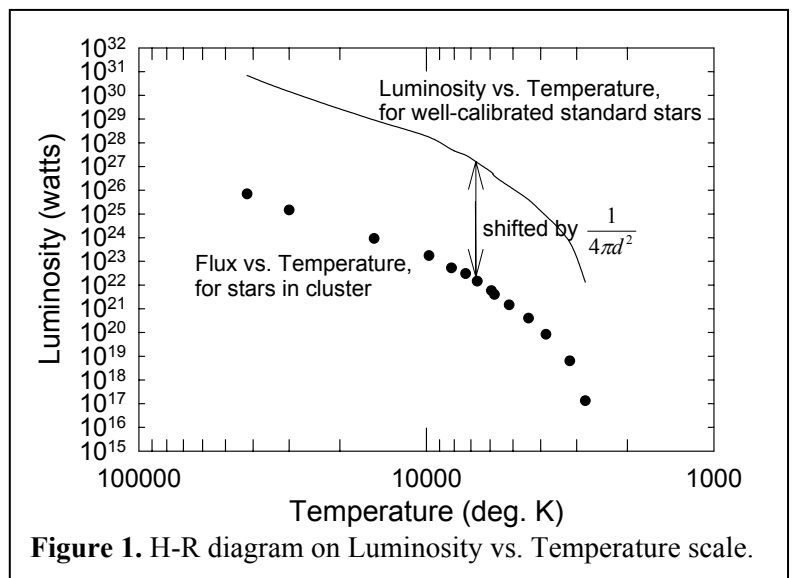
$$d = \sqrt{\frac{4\pi F}{L}} \quad (2)$$

But how do you know what the luminosity L is for the individual stars in the cluster? Some stars are millions of times more luminous than others. The approach used here is to measure the surface temperature of each star, identify which of them are on the main sequence of the H-R diagram, and then for those stars use the well-calibrated relationship between the surface temperature and the luminosity of main sequence stars as a means to work out their luminosities. Then you are all set to use equation (2) to calculate the distance.

However, we will go one step better than that and use a graphical method to average together the ratio of F/L for a large number of stars in the Pleiades. The reason for doing that is to average out small errors in the measured fluxes and in the calibration of the main-sequence luminosities. At the same time, this technique will make it easy to reject Pleiades stars which are *not* on the main sequence.

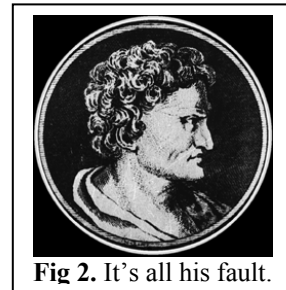
Figure 1 illustrates the basic method. The solid line is a fully calibrated H-R diagram, plotted as luminosity vs. surface temperature. The dots are a sketch of the points representing the individual stars in a hypothetical star cluster, but now plotting as the y-coordinate the observed flux rather than the luminosity. Since all of the stars in the cluster are effectively at the same distance from us, their luminosities have all been multiplied by the same factor of $1/(4\pi d^2)$ to become the fluxes which we measured. So if we can find the numerical factor by which we need to scale the y values of the cluster stars to make their main sequence match the one from the standard calibration, that will tell us the value of $1/(4\pi d^2)$ and hence the distance d to the cluster.

The approach described above is very straightforward, except that there are a few complications having to do with the history of astronomy.



3. The Apparent and Absolute Magnitude Scales

Back around 150 BC, the Greek scientist Hipparchus (who we met earlier in relation to his discovery of precession) catalogued all of the stars that he could see in the sky. This included recording how bright they were. Hipparchus innocently thought up an arbitrary brightness scale in which he designated the brightest stars as magnitude 1 (for “first ranked”) ranging down to a ranking of magnitude 5 for the stars that he could barely see. Unfortunately, this froze into astronomy for all time a brightness scale that runs *backwards* to what intuition would tell us... smaller numbers mean *more* flux, rather than less flux as you might expect. The other unfortunate fact, that only became clear some 2000 years later, is that human eyes don’t respond to increasing flux in a linear way. They respond logarithmically.



Consumer Warning. Please try not to go into shock as you read the following sections. But this is a science lab course in astronomy, and astronomers use the logarithmic “magnitude” scale. I’ve put the whole story in here for completeness, but you only need to follow it well enough to figure out is how to do Part A of the homework. Read the following material, give the homework a try, and then see a TA if you need help.

A reminder about logarithms. The logarithm of a number is the power to which some base number must be raised to equal the number in question. Here we will use only base-10 logarithms, often written as

$$a = \log_{10}(x). \quad (3)$$

The log value a is the power to which 10 must be raised to equal x . That is

$$10^a = x \quad (4)$$

Since $10^0 = 1$, $\log_{10}(1) = 0$. Or given that $10^2 = 100$, we see that $\log_{10}(100) = 2$. Etc. The powers of 10 do not need to be exact integers. For instance, $10^{5.3} = 199,526.23$, so $\log_{10}(199,526.23) = 5.3$

A key point: an important contrast between working with logarithms vs. working with normal numbers is that when you add logarithms, it is the same as multiplying normal numbers together, and when you subtract logarithms it is the same as dividing normal numbers. So if we have any two numbers a and b :

$$\log(a) - \log(b) = \log_{10}\left(\frac{a}{b}\right) \quad (5)$$

One side-benefit of all this is that when you are trying to plot numbers that cover a very wide range of values, it is often much easier to read the plot if you use a logarithmic scale, as in Figure 1. Part A of the homework is aimed at refreshing your memory about the basic properties of logarithms, so if you are a little fuzzy about all this, you will be glad to know that you will get some practice soon.

Magnitudes. Suppose that we have two stars of different brightness. When the magnitude scale was finally calibrated following the invention of photocells, it was found that if the magnitude of Star 1 is 2.5 magnitudes larger than that of Star 2, it means that we are receiving 10 times less flux from Star 2 than from Star 1. If instead the magnitude of Star 2 is 5 magnitudes larger than that of Star 1, then we are receiving 100 times less flux from #2 than from #1. The correct mathematical expression turns out to be

$$m_1 - m_2 = -2.5 \log_{10}\left(\frac{F_1}{F_2}\right) \quad (6)$$

There is a minus sign on the right-hand side of equation (5) so that larger magnitudes will correspond to fainter objects (thanks, Hipparchus).

Apparent magnitudes. We see that differences in magnitudes are just a logarithmic way to express ratios of brightness. If this is used with the apparent brightness (or fluxes) of two objects, the magnitudes are called apparent magnitudes. The apparent magnitude scale has been calibrated so that one particular bright star somewhere in the sky, for example Star 2 in equation (5), has an apparent magnitude of $m_2 = 0$. If we put that value into the equation, then the apparent magnitude of any other star just expresses the ratio of the flux that we receive from it to the flux F_2 that we receive from that standard star.

Absolute magnitudes. But what about the intrinsic, or absolute, brightness of stars? This is their luminosity L . This is handled in the magnitude scale by defining the absolute magnitude of a star to be the apparent magnitude that it would have if it were moved to an arbitrarily chosen standard distance. That standard distance is 10 pc. So if the star in question is closer than 10 pc, we would see the flux from it decrease if were to be moved out away to the standard distance, so its absolute magnitude would correspond to the magnitude of a fainter star... i.e. the absolute magnitude would be a larger number than the apparent magnitude. Conversely, if the star in question is farther away than 10 pc, its absolute magnitude would be a smaller number than its apparent magnitude because the star would appear brighter to us if we moved it in to the standard distance of 10 pc.

One last step. Now we need to convert the difference between the apparent and absolute magnitudes into a measure of distance. The usual convention is to designate the apparent magnitude by m , and the absolute magnitude by M . So now equation (6) can be taken through the following steps

$$m - M = -2.5 \log_{10} \left(\frac{F_d}{F_{10pc}} \right) = -2.5 \log_{10} \left(\frac{10^2}{d^2} \right) = -5 \log_{10} \left(\frac{10}{d} \right) \quad (7)$$

where F_d is the flux received from the star at its true distance d , and F_{10pc} is the flux that would have been received from the star if it were at a distance of 10 pc. The third step in Eq. (7) uses the fact that $F \propto 1/d^2$, and the last step uses the math relation $\log_{10}(a^2) = 2 \times \log_{10}(a)$. Equation (7) can be solved for the distance d to find that

$$d = 10 \times 10^{\frac{(m-M)}{5}} \quad (8)$$

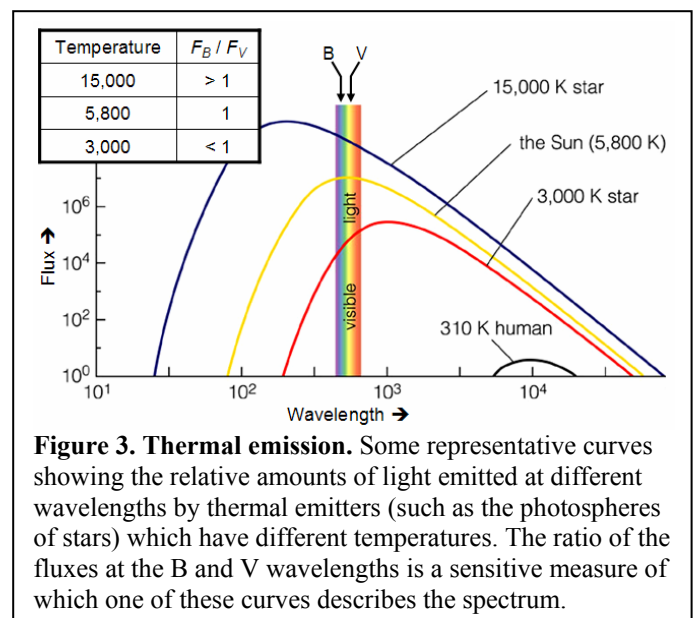
where m = the apparent magnitude, M = the absolute magnitude, and d = the distance in parsecs. At long last, equation (8) is the one that we need for this lab exercise.

4. Back to the Pleiades

For the lab exercise we are going to give you an H-R diagram that plots the absolute magnitudes (M) of standard main sequence stars along its y axis, instead of using L . Then you will simulate using a device called a *photometer* to measure the apparent magnitudes (m) of main-sequence stars in the Pleiades cluster and plot them onto another H-R diagram. Next you will slide one diagram over the other (analogous to what is shown in Figure 1) until the Pleiades main sequence sits on top of the standard main sequence. This will tell you the value of $(m-M)$, and from that you will use equation (8) to calculate the distance d .

A photometer is just a fancy version of a photocell, mounted on the telescope. It is capable of measuring the brightness (apparent magnitude) of stars to high accuracy in a short amount of time. Colored glass filters can be inserted in front of the photocell. These transmit only narrow ranges of wavelength, so the star's brightness can be measured at a series of different wavelengths.

The only remaining twist in the plot is how to measure the surface temperatures. You will use the photometer to measure the apparent magnitudes of each star at two different wavelengths called B (= blue) and V (= visual, actually yellow). The difference $m_B - m_V$ is in magnitude units, so it is really telling us F_B / F_V , the ratio of the star's flux at the two wavelengths. The apparent magnitudes through the B and V filters are usually just designated "B" and "V". The magnitude difference B-V (= $m_B - m_V$) is called the color of the star, and is a direct measure of the star's surface temperature (Fig. 3 shows why). Therefore,



we can use the color as the x-axis on an H-R diagram. Figure 4 shows the same standard calibrated H-R diagram that is used for the solid curve in Figure 1, but now on these new absolute magnitude vs. color scales. This is the H-R diagram that you will use to find the distance to the Pleiades cluster.

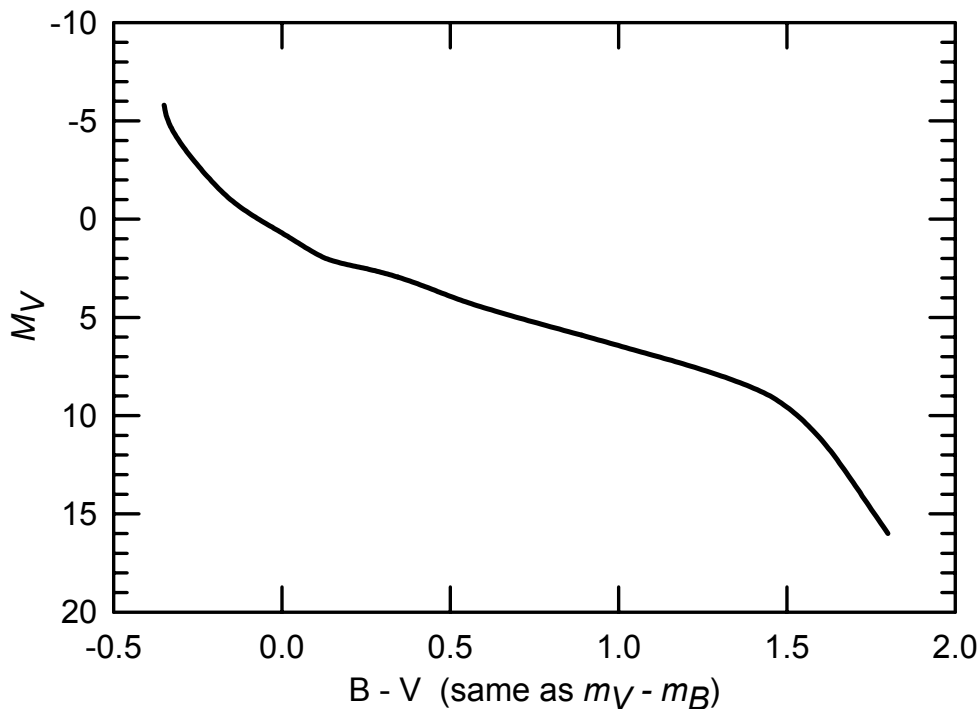


Figure 4. Calibrated H-R diagram showing the main sequence plotted as the absolute magnitude in the visual filter, M_V , vs. the temperature measure $B - V$ (which is the color of the star).

5. Using the Simulated Telescope and Photometer.

As was the case last week, you will use the CLEA telescope simulator program, and you will team up with a partner for this lab. Here are the steps for operating the telescope. Steps (a) through (g) are identical to steps (a)-(h) from last week, except that the exercise is called “Pleiades Photometry” on the Windows Start menu, and the Pleiades cluster is the only choice of star fields:

- Log into the computer using either your or your partner’s MSU NetID (it doesn’t matter which ID you use).
- On the Windows start menu, select Course Software | CLEA | **Pleiades Photometry**
- After the CLEA window appears, click File | Run. The window will change to show the telescope controls, and a box will pop up saying you have control of the MSU 24-inch telescope.
- You are seeing the inside of the dome, so you have to click the “Dome” button to open it.
- Now you can see stars, but they are drifting past the telescope as the Earth turns. Click “Tracking” to turn on the Right Ascension drive motors.
- You should see the Pleiades star cluster through the wide-field viewer. You can see way more stars than

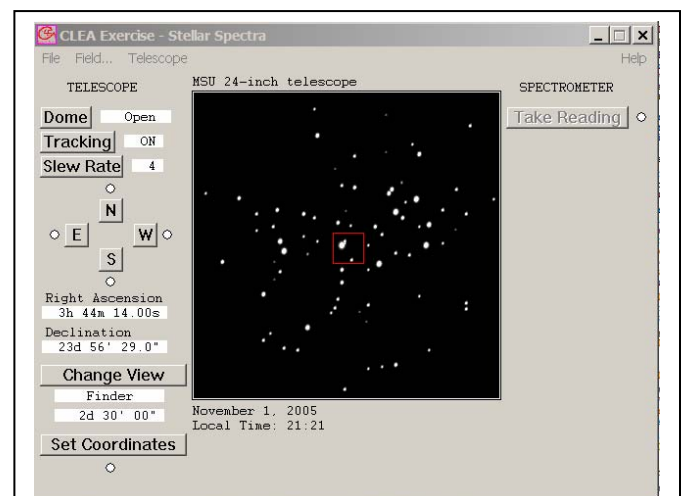


Figure 5. The Telescope Control window, showing the wide-field view of the Pleiades.

just the “Seven Sisters” because you are looking through a good-sized telescope.

- (g) Refer to the answer sheet, which the TA will have passed out at the start of the lab session. It includes a list of Right Ascension (RA) and Declination (Dec) coordinates for the stars that you need to observe. To slew to the first star, you have two choices.
 - a. You can click on the N, S, E or W buttons and the telescope will move in that direction. The “Slew Rate” button adjusts how fast it moves. This is convenient if you know which star is which on the view of the sky.
 - b. But you probably don’t know which star is which, so click on the “Set Coordinates” button and type in the RA and Dec that you wish to move to. This is how it is done on modern research telescopes.
 - c. When the telescope arrives at its target, you will again see the wide-field view of the sky. You may want to center the star up using the N,S,E,W buttons as in (a), but it probably is not necessary.

From here on, it’s different from last week. You will measure the light with a photometer, rather than with the spectrograph you used last week.

- (h) Now click on “Change View”. You will see the magnified view looking down at the photometer’s entrance aperture, which is represented by a red circle. **Sky Reading:** The entrance aperture is quite large, to make sure that all of the star’s light will go into the photometer and be recorded. But this means that a lot of background light from the Earth’s atmosphere is also recorded. Before measuring the first star, you need to use the N,S,E,W buttons to guide the star well away from the entrance aperture, and then measure the sky brightness where there is no star. This sky measurement (or “reading”) will automatically be subtracted from all of the star readings.

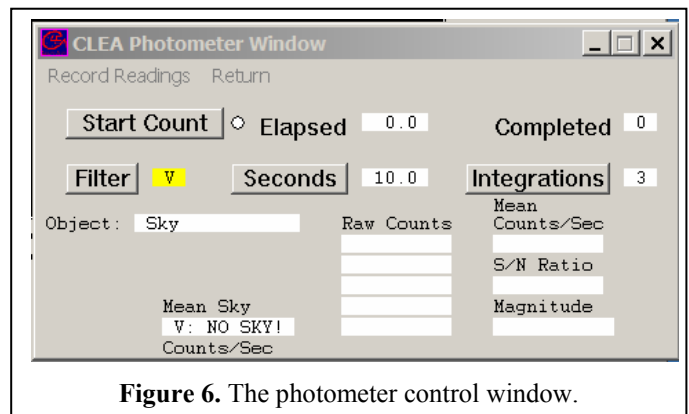


Figure 6. The photometer control window.

- (i) Click on “Take Reading” to bring up the CLEA Photometer Window (Fig. 6).
- (j) The Object should be listed as “Sky”. If instead it shows the name of a star, it means that CLEA thinks the star is in the entrance aperture, in which case you should cycle back to step (g) and then guide the star farther away from the entrance aperture this time.
- (k) Click the Start Count button. The photometer will automatically cycle through a series of readings, the number of which is set by the Integrations button, with each reading being for the amount of time set by clicking the Seconds button. The default values of 10 seconds and 3 integrations are good for the sky and for all but the faintest stars.
- (l) Once the three integrations have finished, you will see that the Mean Sky value is filled in. Now click on the Filter button to select a different filter. For this exercise, you will take data through only the V and B filters. Skip over the U filter choice.
- (m) Once you have taken sky measurements in both the V and B filters, click on “Record Readings” in order to save your measurements. When the Photometric Data box (Figure 7) pops up, just click on “OK”. There is no special need to enter remarks.
- (n) Now click “Return” in the Photometer Window, to get back to the telescope control window.
- (o) Use the N,S,E,W buttons to center the star in the aperture (you may have to decrease the Slew Rate). Unlike the real thing, in this simulation you can still see the star when it is in the aperture. If you don’t get it in the aperture, you will not get any light from the star when you try to measure its brightness.

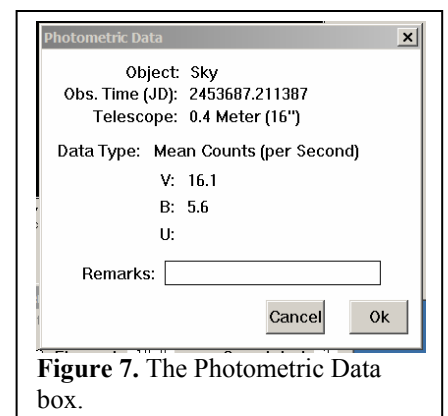


Figure 7. The Photometric Data box.

- (p) Set the Filter, Seconds and Integrations as needed, then click on Start Count. Again, just use the B and V filters. You can do them in either order. To see if your combination of Seconds and Integrations was OK, wait until all of the integrations have been completed and look at S/N ratio (right-hand side of the Photometer Window). **You need to get a S/N (signal/noise) ratio of at least 100.** This corresponds to a total number of counts, adding together all of the integrations, of somewhat over 10,000. If the S/N is too low, change the combination of Seconds and Integrations so that you will get enough Raw Counts to achieve the needed S/N, and redo the measurements. **You will lose points in this assignment if your answers are not sufficiently accurate.**
- (q) Repeat (p) for the other filter.
- (r) Click on Record Readings. But this time, before clicking “OK” after the Photometric Data box pops up, copy the Object name and the B and V magnitudes into the appropriate columns in your answer sheet. Then find the difference B-V (using either a calculator or your brain) and enter that into the last column. You probably can work more efficiently if one partner runs the telescope/photometer, and the other partner fills in the answer sheet including calculating B-V as you go. If you forget to write something down, don’t panic. You always can see the results for all of the stars you have measured by returning to the telescope control window and clicking File | Data | ReView.
- (s) Click “OK” to close the Photometric Data window if you have not already done so. Move to the next star as in step (g) and repeat steps (o) through (r). Do this for all of the stars that you need to observe. Trade off with your partner half-way through. When you are done, go on to the “Distance Measurement” step, below. Note that you only needed to measure the sky once at the start, before you measured any of the stars.

6. Distance Measurement

Each partner should now plot the B magnitude vs. the (B-V) color onto the H-R diagram that is on your Report Write-Up Sheets. Then place your Report Write-Up sheet over the H-R diagram in Fig. 4 of these instructions, and slide the top sheet up and down until your measured main sequence lies on top of the Standard main Sequence. Compare the y axes of the two plots to find the difference ($M-m$) between the absolute and apparent magnitudes. Use that difference in the way described in Section 4 to calculate the distance to Pleiades cluster. Enter your result in the blank space on the Report Write-Up sheet, and answer the remaining questions on the sheet.

7. Grading

Your answer sheet is shared between you and your partner. The points you earn there will count as clicker points for this week. We will grade on accuracy, and you will lose points if for each measurement you did not achieve the accuracy of about 1% that comes from $S/N = 100$. When you compute B-V, be sure to do it correctly.

Your Report Write-Ups will be graded separately for each partner (but feel free to consult with each other as you fill them out). We will grade you for accuracy in your distance determination, and then the essay questions will be graded on whether or not you convince us that you understand what you have done in the lab exercise.

BE SURE TO LOOK AT THE HOMEWORK QUESTIONS ON PAGE 7

8. Homework

The homework this week is divided into Parts A and B, which appear as two separate Angel assignments. You must submit *both* of them by 2PM on the day of the lab meeting. Your scores on the two parts will be added together to form your homework grade for this week.

PART A – Practice with logs, magnitudes, and distance measurements.

You will need a calculator capable of taking logs and either antilogs, or of raising 10 to an arbitrary power. **You should bring this same calculator with you to the lab session.**

In the worst case, you can use the calculator that is on the Windows Start menu under Start | All Programs | Accessories | Calculator. It is also available during the lab session. If you do use it, you should click on View | Scientific. Then use the “log” and “x^y” keys. But if you have a separate calculator that will do the job, you will probably be much happier using that instead of the Windows thing.

For the Angel exercise, you will be asked to do some straightforward computations just to remind you of how logs and antilogs work, and of how magnitudes work, culminating in getting some practice solving equation (8).

This exercise will be graded automatically as soon as you submit it, and you can almost instantly see how you did, and see the correct answers.

You can submit this as often as you wish up to the deadline, but each time you have to start all over and you will be presented with a new set of numbers to use in your calculations.

PART B – Essay and short answer questions.

Do this part like you did last week... the Angel answer sheet has only one blank essay box, so that you can prepare your answers off-line and then just cut and paste them into the answer sheet in one operation. As last week, start each answer by giving the question number (Q1., Q2., etc), and separate the questions with blank lines.

Q1. Why can we plot the stars from the Pleiades cluster onto an H-R diagram using just their measured fluxes, without having to individually calculate a luminosity for each one as in equation (1)?

Q2. What is the apparent magnitude a measure of?

Q3. What is the absolute magnitude a measure of?

Q4. Why does the difference between the B and V apparent magnitudes tell us the surface temperature of a star?