Astr 423, Spring 2019

Homework 8: the astrophysical distance ladder

1 What we did before

In Homework 1 we started our work on the astrophysical distance ladder: the result of that work was the distance to one of the closest open clusters, namely the Pleiades. We will adopt a Pleiades distance of 120 pc.

2 Next step: comparing clusters

We have collected photometry of several stars in the Pleiades and in another, more distant open cluster: NGC 6087. The data are given in ascii files cluple.dat and clu6087.dat.

Since the stars in a cluster are all at essentially the same distance, we find a main sequence even if we plot just the apparent magnitudes as a function of the $(B-V)$ color. This is very useful for our "ladder project". Unless the chemical compositions are very different, we expect the main sequences of different clusters to have the same absolute magnitude for each intrinsic color $(B-V)$. Then any difference in the apparent magnitudes can be immediately translated into a difference in the distances. To know the trigonometric parallax of one cluster is then enough to get the distances to all clusters with well-defined main sequences in the (apparent magnitude) vs. $(B-V)$ diagram. The use of the main sequence as a "standard candle" is a typical example of an astrophysical method of distance determination.

In our application of the ladder we consider clusters located at much larger distances, and soon we find it necessary to take into account the existence of matter between the stars: especially dust, which produces a certain degree of obscuration or extinction. We need to correct the observed magnitudes, like V, to the value they would have in the absence of interstellar extinction. This can be done because of the properties of interstellar extinction:

when expressed in magnitudes, it is roughly inversely proportional to wavelength. The extinction is therefore stronger at shorter wavelengths, and this produces a "reddening" of the stellar light. We measure the reddening and then calculate the corresponding amount of extinction. For example, if we call $E(B-V)$ the reddening or "color excess" suffered by the color $(B-V)$, empirical studies have shown that the extinction A_V in magnitudes is given in many cases by

$$A_V = 3.1\ E(B-V)$$

which allows us to calculate V corrected by extinction: $V_0 = V - A_V$. We can estimate the $E(B-V)$ using the two-color diagram, $(U-B)$ plotted as a function of $(B-V)$. Using colors, which are in fact magnitude differences, distances do not play a role. In the case of a cluster, the observed position of the upper branch of the main sequence lies to the right and below the position of an unreddened main sequence. The length of the displacement along the reddening line that is needed to put the observed upper branch on top of the unreddened one allows us to get the value of $E(B-V)$.
After correcting for the effects of interstellar extinction, we can go back to the V vs. $(B-V)$ diagram and obtain the distance modulus difference between two clusters directly from how many magnitudes we need to displace one main sequence until it coincides with the other.
Such is the work we need to do with our photometric data on the Pleiades and NGC 6087. The result will be a distance for NGC 6087. We selected this cluster because one of its members is a cepheid variable.

3 Cepheids

After we have collected the distances to many clusters, we can obtain the intrinsic brightnesses of many more stars (all those that belong to the clusters). Having collected so many stars we have a good chance to get a few of those stars that belong to less populated regions of the luminosity-temperature (or luminosity-color) diagram. These stars have evolved away from the main sequence, becoming more luminous. They are less frequent than main sequence stars because they do not spend much time in their new evolutionary stage. We call these bright evolved stars "giants" or "supergiants". The fact that they are very bright means that we can see them even if they are very distant. Unfortunately they do not have all the same intrinsic brightness.

However, if we can find a way to know how their intrinsic brightness depends on other, easily observable properties, then we can use them as another step in our distance ladder.

Nature has provided us with a very useful "instability strip" across the luminosity-color diagram. In fact there are several such strips, but let us keep things as simple as possible. Whenever a star enters this instability strip, in its evolution away from the main sequence, it begins to pulsate, in a similar way as a pendulum keeps oscillating as it swings past the position of minimum potential energy in alternative directions.

Probably the star would prefer to stay quiet, but once it enters the instability strip it is forced to pulsate. And as soon as the star leaves the instability strip, the pulsations are damped and stop. The pulsation produces periodic changes in the size and the surface temperature of the star, and therefore also the stellar brightness varies, with a period of several days or weeks. A few centuries ago, astronomers noticed a few bright stars pulsating in this way, and after some time decided to call them "cepheids" in honor of one of the first known cases, Delta Cephei. The theory of stellar pulsation tries to explain this behavior, but we do not need to discuss it right now. What we need to know is that the period of pulsation depends on the inverse of the square root of the density in the star: the denser the star, the shorter is the pulsation period. It can be shown that this relation implies the existence of a period-luminosity relation: the longer the period of pulsation, the more luminous is the star. There are many kinds of pulsating stars, but the cepheids are a very homogeneous group, with extremely stable periods, very similar light curves, and following a very well-defined period-luminosity relation. It is comparatively easy to discover cepheids, and once you know the period of the light variation you have information about the luminosity of the cepheid. You may wonder how could astronomers decide that cepheids obey a period-luminosity relation before it was possible to get the distances to many of them. The reason is that many cepheids were discovered in a satellite galaxy of our Milky Way: the Large Magellanic Cloud (LMC). Although the discoverers did not know the distance to the LMC, they knew that all the cepheids in this satellite galaxy are at the same distance from us. So in fact they discovered a relation between the average apparent magnitudes and the periods of the LMC cepheids. Only much later it was possible to get the intrinsic brightnesses of just a few cepheids in Milky Way clusters, and thus an accurate distance to the LMC could be finally calculated, some 50 years after the LMC cepheids were discovered.

With current technological advances (the Hubble Space Telescope and 10-m telescopes) we can discover cepheids at distances up to 25 or may be 30 Mpc, and there has been a lot of activity in the determination of distances to galaxies where cepheids can be found. Using the distances to all these galaxies we will be able to understand the properties of other brighter astrophysical objects (for example supernovae), and a new step in the distance ladder will become firmly established.

4 Distances and cosmology

Some people may find it difficult to imagine how essential good distances are for the development of our scientific ideas about the Universe. Before 1924 (when cepheids were discovered in the Andromeda spiral galaxy) astronomers did not know if galaxies are small satellites of our Milky Way, our Galaxy being the dominant constituent of the Universe, or if other galaxies are (as we know now) independent accumulations of luminous and dark matter, of comparable importance to our own galaxy, and at much larger distances from us than previously thought. The realization that we live in a Universe of galaxies triggered explosive advances in Astrophysics and led to the discovery of the isotropic expansion of the Universe and the modern development of Cosmology. We will make a very short excursion into Cosmology. We will estimate the Hubble parameter H_0, in km/s per Mpc, which gives the rate of expansion of the Universe. The inverse of H_0 can be taken as a very rough estimate of the time elapsed since the Universe was all together in the "big bang". In order to estimate H_0 we need to know (a) the radial velocity of a galaxy and (b) its distance. As a final challenge, you will be asked to estimate the age of the Universe.

5 What we plan to do

In this homework we provide an elementary introduction to the problem of distance determinations to nearby galaxies, using the properties of cepheid variables. The classical cepheid variables are universally acknowledged as the most reliable distance indicator for distances up to about 25 Mpc. What we use as standard candle is the period-luminosity relation of the cepheids. The calibration of cepheid luminosities is difficult because of their low space density, i.e. there are none of them sufficiently close to the Sun for a reliable trigonometric parallax to be measured. Therefore we are forced to proceed in several steps. Of the several procedures that can be followed we have selected this one:

(A) The parallax of the Pleiades open cluster permits to obtain its distance.

(B) Having found cepheids in other, more distant clusters, we measure the distance moduli of these clusters relative to the Pleiades by superposing the unevolved sections of the cluster main sequences. Here we must make corrections for the interstellar extinction and reddening. We will apply this procedure to the particular case of the open cluster NGC 6087, to which the cepheid S Normae belongs.

(C) Knowing the average apparent visual magnitudes of other cluster cepheids, and the distance moduli, we obtain the absolute visual magnitudes of the cepheids. Plotting them as a function of the pulsation periods, we find the period-luminosity (or period - absolute magnitude) relation. But we see that most of these local cepheids with reliable distances have rather short periods, and we would prefer to have our period-luminosity relation defined by many long-period cepheids, which are brighter and therefore can be detected at larger distances from us.

To solve this, we compare the local cepheids with those in the Large Magellanic Cloud (LMC), which have a more convenient number of long periods. We obtain the distance to the LMC and use it as our standard candle: we measure distances to more distant galaxies relative to the distance of the LMC.

(D) We apply our method to a galaxy in the Fornax cluster: NGC 1365. The full work would involve the following steps:

(a) acquisition of CCD images of the galaxy at several epochs.

(b) image processing, discovery of variable stars.

(c) photometric reductions, magnitude estimates.

(d) period determination and confirmation as cepheids.

(e) estimation of average magnitudes and colors on a standard system.

(f) correction for extinction and distance estimate, using the LMC cepheids as standard candle.

Since we do not have enough time for the full procedure, this last phase of the homework will be restricted to steps (d) to (f). In the final step we estimate the Hubble parameter H_0 and the age of the Universe.

6 Description of data, activities and tasks

Most of the actions described below can be performed using the IDL programs listed at the end of each subsection. Each subsection has a list of tasks to be accomplished. Please verify that you have done everything requested.

Step 1. Consider the cepheid S Normae, located in the cluster NGC 6087.
Period = 9.75 days
Average Visual magnitude = 6.42 (apparent magnitude)
Color excess $E(B-V) = 0.18$
The interstellar extinction correction is $A_V = 3.1\ E(B-V)$. Calculate the average visual magnitude V_0 that would be observed in the absence of interstellar extinction.
In order to obtain the absolute visual magnitude we need the distance to the cluster. We will estimate the difference between the distance moduli of NGC 6087 and the Pleiades by comparing their main sequences. Run the IDL program "clusters". We have files with UBV photometric data for the Pleiades (50 stars) and NGC 6087 (29 stars). For this comparison we must use corrected stellar magnitudes, because each cluster suffers a different amount of reddening and therefore of extinction. The colors $U-B$ and $B-V$ can be used to estimate the amount of reddening correction to be applied. We do not need the individual reddenings for each cluster; it is enough to know the difference in $E(B-V)$. We determine this difference by comparing the positions of the selected stars in the $(U-B)$, $(B-V)$ plane. There will be a certain amount ($\Delta E(B-V)$) that will force the stars from both clusters to occupy the same place in the two-color diagram. We will estimate this $\Delta E(B-V)$ by trial and error.
Having obtained the $\Delta E(B-V)$ we can calculate the ΔA_V, which must be 3.1 times the $\Delta E(B-V)$. After applying this differential extinction correction, we assume that the only difference that remains between the main sequences of the 2 clusters derives from their different distances to us. We will estimate the difference in distance moduli by trial and error until we get a good superimposition of both main sequences. Please estimate the uncertainty in the distance modulus difference, which has two main sources: the error in the ΔA_V, and the error in the main sequence comparison, due to the natural dispersion and the errors in the photometry.
At the end of this step we calculate the distance modulus of NGC 6087 and express the distance in parsecs. We also calculate the average absolute visual

magnitude of S Normae. How many times brighter than our Sun is this star? Remember that the absolute visual magnitude of the Sun is +4.8. What would be the average apparent visual magnitude of S Nor at a distance of 25 Mpc, assuming no interstellar extinction? At what distance would a star like our Sun have that same apparent magnitude?

IDL program: clusters.pro; Data: cluple.dat, clu6087.dat

Summary of tasks: at the end of this step you must have an estimate of the following quantities: the average visual magnitude of S Nor that would be observed in the absence of interstellar extinction, the $\Delta E(B-V)$ between the Pleiades and NGC 6087, the difference between the distance moduli of the Pleiades and NGC 6087, the resulting distance modulus of NGC 6087, its distance in pc, the average absolute visual magnitude of the cepheid S Nor, its luminosity in solar luminosities, its average apparent visual magnitude if it were at a distance of 25 Mpc, and the distance at which the Sun would have that same apparent visual magnitude.

Step 2. In principle we should repeat the previous work for each of several cepheids that belong to open clusters or associations, but we will simply take the results from the literature, e.g. Feast and Walker 1987. We have a file cepgal.dat with the periods and absolute visual mags of 19 cepheids. Using the program "zeropo" we plot these numbers (they appear as plus signs) and add our result for S Normae, which should appear as a diamond and fall of course on the period-M_V relation if all went well. Now we introduce the LMC cepheids: we will determine interactively the distance modulus to the LMC by adjusting (trial and error) the LMC period-m_V relation to our local Galactic period-M_V relation. The LMC cepheids will appear as squares in our plot. We use files plr.dat and spc.dat with data for LMC cepheids taken from Madore (1985). We must adopt a value for the $E(B-V)$ of the LMC cepheids: take 0.12 (the program corrects for extinction), and then estimate the LMC distance modulus and its uncertainty.

IDL program: zeropo.pro; Data: cepgal.dat, plr.dat, spc.dat

Summary of tasks: at the end of Step 2 you must have an estimate of the distance modulus of the LMC. Express the corresponding distance in pc.

Step 3. Now we are ready to jump to the Fornax cluster of galaxies. We will use data on some of the 43 cepheids discovered with the HST by Silbermann et al. (1999). For your convenience and comfort we have prepared 10 files, one for each variable star. Their names are cepv#.dat, with # from 5 to 31 (not all the variables in Silbermann et al. (1999) were used). Each file gives the visual magnitudes at certain times of observation. This information is used by the program "lafkin" to test all possible periods, by the method of Lafler and Kinman, and find the period that produces the smoothest light curve, causing the function "theta" to become minimum. You have to verify if the selected period produces a typical cepheid light curve; the program is not powerful enough to make this evaluation without your help, and it might happen that the discovered variable is not a cepheid but, for example, an eclipsing binary. Or it might happen that the program finds more than one suitable period, in which case you have to select the best one. Sometimes the best period does not give the most convincing light curve, and a slightly worse period can be selected if its light curve looks better.

After you are convinced that each variable is a cepheid, please estimate on the light curve its average visual magnitude. Also give an estimate of the average infrared (I) magnitude, using the light curves provided in the work of Silbermann et al. Edit the file n1365.dat and add your results into it: period in days, average V, average I, for each cepheid.

Now we use the last program, "plr", to estimate the distance modulus of NGC 1365 relative to the LMC. Give the name of the file with your data (n1365.dat) and the program will ask for two relative distance moduli: one for the V and another for the I magnitudes. Select them by trial and error until you are satisfied with the fits of both period-apparent mag relations. Note that in this case we have not applied any reddening correction; we are comparing the observed apparent mags. If the cepheids in NGC 1365 suffer more reddening than those in the LMC, we will notice because there will be a difference in the relative distance moduli for V and I; the reason being that the interstellar extinction is weaker in the infrared. If there were a difference between the V and I relative distance moduli, we could estimate what happens as we let the wavelength increase to infinity, because we know $A_I = 0.48\ A_V$, given the shape of the interstellar extinction curve as a function of wavelength (remember, we said before that the extinction is inversely proportional to wavelength, in a first approximation). Bearing this in mind, estimate the delta mag that corresponds to infinite wavelength, and using the LMC distance modulus obtained in step 3 give the distance modulus of NGC 1365 and express the distance in Mpc. Estimate the accumulated uncertainty in the final result.

Knowing the redshift of the Fornax cluster, we could use the distance we have determined to derive the Hubble parameter H_0. However this is not a

good idea because there are uncertainties in the local velocity field (where "local" means now a few tens of Mpc). Therefore we will use the following information: the Coma cluster of galaxies is 5.7 ± 0.5 times as distant as the Fornax cluster, and Coma has a redshift of 7185 ± 60 km/s. With this information plus your distance to Fornax, estimate H_0 and its uncertainty. Finally estimate the age of the Universe ($1/H_0$) and its uncertainty.
IDL programs: lafkin.pro, plr.pro; Data: cepv#.dat, plr.dat
Summary of tasks: at the end of Step 3 you must have a file with the periods and average V and I magnitudes for cepheids in NGC 1365. You must have obtained the distance modulus relative to the LMC, and the final result: the cepheid distance to NGC 1365, with its uncertainty. You must have got also your estimate of H_0 in km/s per Mpc, and its inverse, expressed in years.

7 Suggested bibliography

Silbermann et al. 1999, ApJ, 515, 1 (astro-ph/9806017): The HST Key Project on the extragalactic distance scale XIV. The cepheids in NGC 1365.

Feast and Walker 1987, ARAA 25, 345: Cepheids as distance indicators.

Turner 1986, AJ 92, 111: Galactic clusters with associated cepheid variables. I. NGC 6087 and S Normae.

Lafler and Kinman 1965, ApJS 11, 216: method of period determination.

Johnson and Mitchell 1958, ApJ 128, 31: the color-magnitude diagram of the Pleiades cluster.