Lab 5. Parallax

1 Introduction

Perhaps the most basic and most important question an astronomer can ask concerns distance. Objects in the sky have a large range of apparent brightnesses, but without distance information, we have no way of knowing how bright these objects really are. Distances in the solar system can be determined with great accuracy (one part in 10^8) using a combination of earth-based radar, geometry, and Newton's laws of Gravity, but outside the solar system, our ability to measure distances decreases dramatically. In this lab, we will begin to explore ways of measuring the distances to stars and galaxies. But first, we present a bit of background to the subject.

2 Parallax

The simplest and most direct way of measuring the distance to a star is with trigonometric parallax. Simply put, parallax is the apparent change in the position of an object due to a change in the viewer's position. (For a demonstration of parallax, hold your arm away from your body, and then view your thumb, first with one eye closed, and then the other. The position of your thumb, relative to the background will appear to change, as the perspective defined by your open eye changes.) Since we on the earth are changing our position daily as the earth orbits the Sun, the apparent positions of the stars should reflect this change.

Figure 1 demonstrates the affect. In 6 months, the earth changes its position by 2 astronomical units (2 A.U.) as a result of its motion around the Sun. Because of this, a nearby star must change its position relative to the background stars by some *parallax angle* normally denoted by π. From geometry, the distance from the Sun to the star is related to the parallax angle by

$$d = R \,/\, \tan \pi \tag{1}$$

The Babylonians were the first people to attempt to measure stellar parallaxes. After them, the Egyptians, the Greeks, and the Renaissance scientists all attempted to measure parallax, if, for no other reason, to prove that the Earth revolved around the Sun. (After all, if the Earth moves around the Sun, then parallax *must* exist.) Unfortunately, no stellar parallaxes could be measured until 1848. The reason: the stars are so far away the parallax of even the closest star is extremely small — less than 1 arcsecond (or the size of a dime viewed from 2 miles away). Considering the fact that the atmosphere itself blurs images out by about 1 arcsec, this makes measuring parallax on Earth extremely tricky for the closest stars and absolutely impossible for most astronomical objects. However, at least it simplifies equation (1). For small angles (and this certainly qualifies) $\tan\theta \approx \sin\theta \approx \theta$ (in radians, of course) so equation (1) becomes

$$d = R/\pi. \tag{2}$$

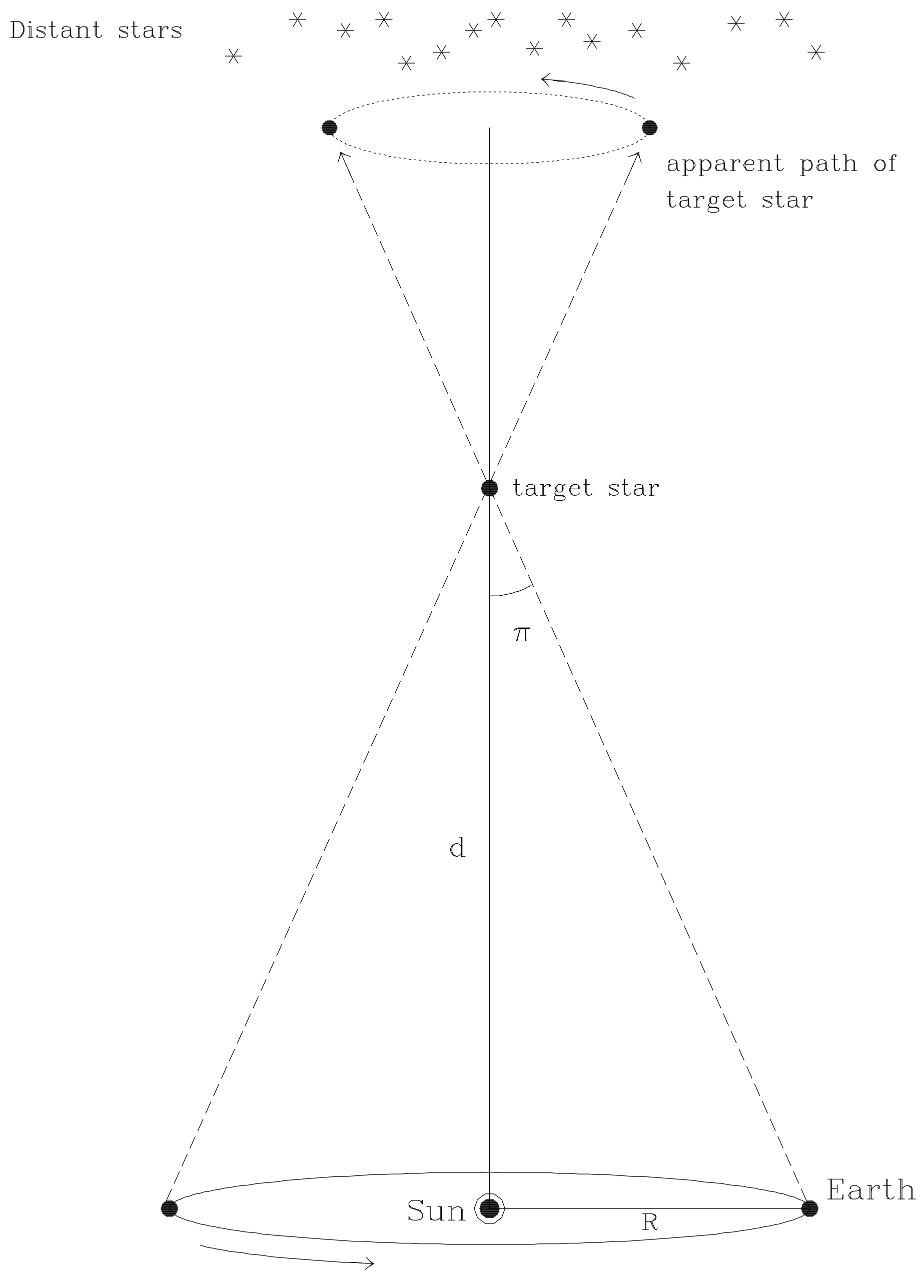

Figure 1: Trigonometric parallax.

Since R, the distance from the Earth to the Sun, is 1 A.U., or 1.49×10^{11} m, a parallax angle of 1 arcsec (1/206265 radians) translates into a distance of 3.086×10^{16} m. Obviously, this is an extremely large distance and awkward to remember. To ease the strain of working with these big numbers, astronomers call this distance a *parsec*. Hence 1 parsec is the distance an object would be at, if it had a parallax of 1 arcsec. Since virtually all determinations of astronomical distances are based one way or the other on measurements of parallax, the parsec (abbreviated pc) is the primary unit of distance in astronomy.

3 Magnitudes and distances

Once a distance is measured, the absolute intrinsic luminosity of a source can be measured. Suppose in some color light, say, 5500 Å, a star is emitting L_V watts from its surface. At a distance d from the star, this light has spread out over a surface area of $4\pi d^2$, hence the amount of light seen is

$$F_V = L_V / 4\pi d^2 \tag{3}$$

F_V is called the stellar flux, and has the units of watts-m^{-2}. When measuring brightness, however, optical astronomers do not often work in units of flux: instead, astronomers use a backward quantity related to the log of the flux, call magnitude, which is defined as

$$m = -2.5 \log F + C \tag{4}$$

where C is some constant that we'll worry about later. With this definition, the brightness of any two stars can be compared to each other. If the flux recorded from Star 1 is 10 times less that recorded from Star 2, then from equation (4)

$$\Delta m = m_1 - m_2 = -2.5 \log F_1/F_2 = 2.5 \tag{5}$$

Note that the brighter the star, the smaller the magnitude. Note also that when you compare two stars, the constant C doesn't matter — it subtracts out. Magnitude differences can therefore be determined over the entire sky, and (theoretically) only one star is needed to define C, which is the zero point of the system. For the record, most magnitude systems use the star Vega to set the zero point, with $m_{\rm Vega} = 0$.

The magnitudes discussed above are *apparent* magnitudes, *i.e.,* how bright stars appear from Earth. From equation (3), a star's apparent magnitude is related to its absolute luminosity by

$$m = -2.5 \log L + 5 \log d + C \tag{6}$$

(I've incorporated the extra constant involving 4π into C.) Once again, you can see that the system works well for inter-comparing two stars. For example, consider a star 1000 pc away. If the star were moved magically moved closer to the earth, say, to a distance of 100 pc, it would naturally appear brighter. How much brighter?

$$\Delta m = 5 \log(1000/100) = 5 \tag{7}$$

Here, we will introduce a definition. To compare the intrinsic luminosities of stars, astronomers define *absolute* magnitude to be the apparent magnitude a star would have *if* it were at a distance of 10 pc. Thus, the relation between the apparent magnitude of a star, m, and its absolute magnitude M is

$$(m - M) = 5\log(d/10) \tag{8}$$

or

$$(m - M) = 5\log d - 5 \tag{9}$$

where the distance is measured in parsecs.

4 The lab

Stars, of course, do not emit the same amount of energy at each wavelength, and the magnitude you measure depends on the wavelength of the observation. A cool star will emit more red light than blue light, thus an experiment which records its blue light will produce a larger (fainter) magnitude measurement than one that measures its red light. Conversely, an observation of a hot star in the blue will produce a smaller (brighter) magnitude than a measurement in the red. The branch of astronomy that deals with measuring the brightnesses of objects is called *photometry.*

There are several different photometric systems used in astronomy today. The most common system is called the Johnson UBV system. It employs three filters, a 900 Å wide ultraviolet filter centered at 3600 Å, a 1000 Å wide blue filter centered at 4400 Å, and a 1000 Å wide visual (yellow) filter centered at 5500 Å. Extremely hot O stars emit more blue light than red light, hence they will have a $(B-V)$ color < 0 ($B-V$ is short for $m_B - m_V$). The very coolest stars M will have $(B-V)$ values greater than 2. As in most other systems, Vega, which is an A0 star, defines the zero point, so for it, $(B-V) = 0$.

This lab will give you some experience with parallaxes, magnitudes, and colors of stars, and challenge your ability to interpret actual data. In the file **parallax.dat** we have collected UBV photometric information for 1998 stars in the solar neighborhood. You can view this file by typing

page /afs/psu.edu/users/m/a/mab22/lab5/parallax.dat

(If you are already in IDL, precede this instruction with a dollar sign.) The first column of the file contains the measured parallax as given in the Yale Parallax Catalog, the second column gives the error assigned to this parallax, column 3 lists the APPARENT V magnitude of the star, column 4 lists the star's $(B-V)$ color, and column 5 gives the star's $(U-B)$ color. As always, you can exit **page** by typing **q**.

Your task is to examine these data and, in the process, learn about stars. You will begin by making a "color-magnitude" diagram, in which stellar absolute magnitude, M_V, is plotted on the y-axis, and stellar temperature, as reflected by $(B-V)$ color, is plotted on the x-axis. (For consistency with the astronomical literature, your diagram will have stellar brightness *increasing* as you go up, and stellar temperature *decreasing* as you go to the right.) You will then examine this plot and try to understand what it is telling you about stars. Is there a relationship in the data? Do all stars obey it? Does the relation change depending on the sample of objects plotted? For example, what does the color-magnitude diagram look like if you plot only those objects whose distances are known to better than 10% (or, in you only want to look at extremely accurate data, 5%). Suppose you restrict your sample to stars with bright apparent magnitudes, say $m_V < 10$. Has the relation changed? Suppose, instead of plotting absolute magnitude versus color, you plot color versus color, as in $(U-B)$ versus $(B-V)$. (If you do this, for consistency with the literature, keep the $(B-V)$ axis the same as before, and put $(U-B)$ on the y-axis, with the small (negative) values on top.) What are these relationships telling you about the stars?

4.1 Procedure

Enter IDL, and read the data contained in **parallax.dat** by typing

.run /afs/psu.edu/users/m/a/mab22/lab5/lab5.pro

This is a very simple program which will read your data into a 5×1998 size array called **data**. You can view this program by typing

$ page /afs/psu.edu/users/m/a/mab22/lab5/lab5.pro

You will now need to perform a mathematical manipulation both to convert apparent magnitudes to absolute magnitudes. You will also need to select sub-samples of data for analysis. IDL can do this very easily. Below are some handy commands that are accessible for these purposes.

- The array **data** contains 5 types of data: parallax, error, V-mag, $(B-V)$ color, and $(U-B)$ color. Rather than work with this array, however, you may find it easier to put each column in a one-dimensional array of its own. For example, if you want to copy the 3rd column of array **data** into a new 1-dimensional array called **vmag**, you can type

  vmag = data(2,*)

  Here, the * tells IDL to get all rows of the column specified, and the number **2** tells IDL to copy the 3rd column. (Remember, IDL does all its counting starting from zero, so the 3rd column you see on your screen corresponds to array column 2.) If, on the other hand, you only want to copy part of a column into the array **vmag** (say, the first 100 elements of column 3), you can type

  vmag = data(2,0:99)

  Obviously, these operations will work on columns as well as rows.

- A useful way to get only part of a larger array is using the **where** command. For example, if you want to know which magnitudes are less than zero, and **vmag** is a long list of magnitudes which are both negative and positive, you can type

bright = where (vmag LT 0.0)

This command copies the indices of all the magnitudes that are less than zero into a new array, called **bright**. The Fortran-style GT, GE, LT, and LE stand for greater than, greater than or equal to, less than, and less than or equal to, respectively. For instance, if only the 3rd, 20th, and 1000th elements of **vmag** are negative, then **bright** will contain 3 numbers: 3, 20, and 1000. You can then use this array to make a new array containing only the bright magnitudes by typing

brightvmag = vmag(bright)

This tells IDL to copy those elements of **vmag** that are at the indices indicated by **bright** into a new array, called **brightmag**.

- Arithmetic operations are easily done with arrays in IDL. If **A** and **B** are pre-defined arrays, then the following commands operate will operate on them and place the results into array **C**.

  C = A + 10.0

  C = A / 2.

  C = A + B

  C = A – B

  C = A * B

  C = A / B

  C = A - 5*B

  C = alog10(A)

  (The last instruction takes the base 10 log of **A**.) Note all these operations effect the entire array. Thus **A / 2.0** divides all the elements in the array by 2. Note also, that if you want to do arithmetic with two arrays (say, **A / B**) both arrays better be the same size.

- Most of the plotting instructions you already know from previous labs. To plot *yarray* vs. *xarray* you type

  plot, *xarray, yarray*

  Unfortunately, IDL isn't very good at picking a default scale for plots, so to get useful plots, you almost always have to specify the limits on your axes. You do this by typing

  plot, *xarray, yarray,* **xrange=[***xmin, xmax***], xstyle=1, $**

  yrange=[*ymin, ymax***], ystyle=1**

  where *xmin, ymin* is the origin of the plot, and *xmax, ymax* is the coordinate of the upper right-hand corner. The arguments **xstyle=1** and **ystyle=1** are needed to force IDL to obey your limits precisely, rather than round them off. (By the way, note the dollar sign at the end of the first line. If you run out of room on a line, type **$** — this tells IDL that the instruction continues on the next line.) To add titles to your plot, try

plot, *xarray, yarray,* **xrange=[***xmin, xmax***], xstyle=1, $**
yrange=[*ymin, ymax***], ystyle=1, title='My Title', $**
xtitle='X-axis', ytitle='Y-axis'

where **title** is the title of the whole graph, and **xtitle** and **ytitle** are the axis labels. Finally, to choose the symbol you want to plot your points with, type

!psym = n

before the plotting instruction. Here, n is an integer between -7 and $+7$. If you experiment, you can see what each **!psym** does.

- Finally, if you want to get a hard copy of your plots type,

  set_plot, 'PS'

  to issue your plotting instructions. When you're finished, type

  device, /close

  and

  $ lpr idl.ps

  This will get the printout. (Be patient — this may take time. If you want to check to make sure something is happening, type **$lpq**. You should see your job listed in the print queue.) Note that between the time you type **set_plot,'PS'** and issue the command **device, /close**, you can make more than one plot They will all be sent to the printer at your **$ lpr** command. Once the plots have been successfully printed, type

  $ rm idl.ps

  to remove the plot file from your disk. Remember, to get back to terminal-plotting type

  set_plot, 'x'