

Stars in Motion

Observational Astronomy

1 Introduction/Background

Stars all move in space. It was observed in the 18th century that the stars are not fixed in space, but are moving with respect to each other. While observing the same area of the sky during multiple time intervals, some stars were found to be displaced with respect to their neighbors.

Not all of their motion will be observable to us; some stars are too far away for us to see their motion, and others are moving too slowly with respect to the Sun. The motion that is observable will have components of motion both along our line of sight and perpendicular to the line of sight. We must observe the Doppler shift to see the line of sight motion, but the transverse (perpendicular) motion can be observed directly.

2 Proper Motion

2.1 Measurement of Proper Motion

The transverse motion across the sky is called *Proper Motion*. This value is given the symbol μ and is measured in arcseconds per year. The unit of measure typically used to describe stellar distance is the parsec (pc), and is defined as the distance at which one astronomical unit (AU) subtends one arcsecond in the sky. So, an angle of μ arcsec at a distance of r pc corresponds to a separation of $r\mu$ AU; proper motion of μ arcsec per year of a star at a distance of r pc corresponds therefore to a velocity of $r\mu$ AU per year.

$$1 \text{ AU} = 1.5 \times 10^{11} \text{ m approximately}$$

$$1 \text{ year} = 3 \times 10^7 \text{ s approximately}$$

$$\text{Therefore } 1 \text{ AU per year} = 5 \times 10^3 \text{ m} \cdot \text{s}^{-1} \text{ approximately}^1.$$

¹Using exact values the result becomes $4.74 \times 10^3 \text{ m} \cdot \text{s}^{-1}$

2.2 Calculating Transverse Velocity

The formula for linear velocity perpendicular to the line of sight of an object at distance r pc which has proper motion μ arcsec \cdot yr⁻¹ is then:

$$U = 4.74 \times \mu \times r \times 10^3 \text{ m} \cdot \text{s}^{-1}$$

The transverse velocity U cannot be calculated unless the distance r of the star is known. The proper motion is more easily measured than parallax, and the number of stars for which proper motion is known is higher than the number for which distance is known². Improved methods of making precise observations of star positions continue to add to the numbers of stars for which distances and motions are available. Velocities of stars in the Milky Way are on the order of $3 \times 10^4 \text{ m} \cdot \text{s}^{-1}$, though some can be as high as $10^5 \text{ m} \cdot \text{s}^{-1}$. The Sun's motion through space with respect to the neighboring stars is $2 \times 10^4 \text{ m} \cdot \text{s}^{-1}$.

3 Measuring Proper Motion with Astrometric Observations

For this exercise you will need to look at astrometric images of a star that show its motion relative to its surrounding star field. The most convenient object to use for this purpose is called Barnard's Star, which has the largest proper motion we can see.

There is an electronic simulation of this star's motion with respect to the star field around it on the Hipparcos Space Astrometry Mission website (<http://www.rssd.esa.int/Hipparcos/>). If you look at the Website Tour and The Fastest Stars there will be multiple links to Proper Motion simulations of the 5 stars with the fastest such motion.

The Java applet that pops up will show a star field centered on the star you are looking for. The star's initial RA and Dec will be listed below the star field. Stars here are shown in red and are false sizes to show the relative magnitudes³. The starting year for the simulation is 2000. This simulation will allow you to observe the proper motion of Barnard's Star and the star field around it in increments of 10, 100, 1000, or more years. By toggling the tails option on, the applet will track the displacement of each star for you. Keep notes of your observations on the exercise sheet.

You will calculate the proper motion of Barnard's Star. To get a reliable measurement of the proper motion of Barnard's Star, we will be looking at a set of photographic plates that show the star's motion during a ten year span. There are two images to download at www.rpi.edu/~hillej/Obs_Astro/Images/:

Barnards_Star_Plate01

Barnards_Star_Plate02

²Annual parallax is the change in a star's position relative to the background of distant stars due to Earth's annual motion around the Sun, from which the star's distance is measured in terms of the dimensions of Earth's orbit.

³The scale at the top of the star field shows the magnitude scale

These images are photographic plates taken of the area around Barnard's Star by the Lick Observatory and were taken 10 years apart. Their horizontal dimensions are 40.5 arcminutes.

Tracking of the star's movement will have to be done in pixels, but converting⁴ the pixels to arcseconds shouldn't be too difficult. In MaxIm DL the overall pixel dimensions of the image will be displayed at the bottom of the image window. The **Information** window will output the pixel coordinates of the start point and end point of any square that is drawn by clicking and dragging the cursor. Using this to measure how far the star has moved with relation to a nearby fixed-position star will probably be the easiest way to find the proper motion. Barnard's Star does move both horizontally and vertically in the image, so you will need to take both components into account.

4 Radial Velocity

4.1 The Doppler Shift

The proper motion of a star describes motion perpendicular to the line of sight. To find the motion along the line of sight, called the *Radial Velocity*, the spectrum of the star must be examined for wavelength shifts caused by the Doppler effect. The Doppler effect is the change of wavelength of light when its source moves along the line of sight with respect to the observer. The change in wavelength is proportional to the relative velocity v in the line of sight according to the formula:

$$\frac{(\lambda' - \lambda)}{\lambda} = \frac{v}{c}$$

where λ is the rest wavelength observed when there is no relative motion of the source, λ' is the wavelength from the moving source and c is the speed of light.

The Doppler formula does not involve the distance of the star; the radial velocity is obtained from the spectrum, irrespective of the distance of the source. For this reason the radial velocities of distant galaxies are observable while proper motion is detectable only for relatively nearby stars in our galaxy.

4.2 Locating Doppler Shifts Using Spectroscopy

To see the necessary shifts in the spectrum of a star, it is important to have recognizable absorption lines to look at. Iron has a great spectrum for this purpose as there are hundreds of absorption lines contained in its spectrum, and the wavelengths of these lines are very precisely known. Many stars show iron absorption lines in their spectra; for these stars the Doppler shift is found by looking at the displacement of the iron lines in the star's spectrum from where we know them to be when the source is at rest. It's not easy to tell by looking at a spectrum from a moving source which lines correspond to absorption by which molecules

⁴Note that the dimensions of the two images have slightly different pixel counts. You can ignore this and use the value for one of the images, or take the difference into account in any way you like.

Table 1: Wavelengths of lines in the spectrum of the star. (Lines c and d are very close together.)

| Line | λ (nm) | |
|------|----------------|------------|
| a | 388.90 | Hydrogen |
| b | 393.38 | Calcium II |
| c | 396.86 | Calcium II |
| d | 397.01 | Hydrogen |
| e | 410.17 | Hydrogen |
| f | 434.05 | Hydrogen |

without some extra knowledge. The lines in the stellar spectra are recognized from their positions relative to each other; for example, the spectrum of an A type star is dominated by the series of transition lines of hydrogen (the Balmer lines) which have an unmistakable pattern.

4.3 Measuring Doppler Shift with Photographic Plates

You will need to retrieve the file `Doppler_spectrum.jpg` from `www.rpi.edu/~hillej/Obs_Astro/Images/`.

The image contains two spectra; the image of one spectrum is horizontally cut in half by the other. The thin, light colored band running down the horizontal centerline of the image is the absorption spectrum of the (spectral type A) star being observed. Dark vertical lines in this band represent absorption in the star, and are the lines that are of interest for calculating Doppler shift. These lines are labeled with lower case letters on the image. The other parts of the image are the two dark regions, with vertical white lines, that are above and below the absorption spectrum. These two parts of the image are actually just parts of the same spectrum, but it's being cut in half by the emission spectrum. This larger spectrum is that of emission lines for iron. We are interested in using iron in this case so we can get a good wavelength scale from which to interpret the wavelengths of the shifted lines. The lines that are labeled with capital letters are selected emission lines from the iron source, the wavelengths for which are provided in Table 2; the lines labeled with lower case letters are absorption lines from the observed star (These are the Doppler shifted lines, so you will be calculating their wavelengths). The wavelengths of these lines, *if the source star was not moving*, are given in Table 1. So, you will be calculating the shifts of the lines in the image from their rest wavelengths in Table 1.

Though the measurement of radial velocity is very simple in principle, it is less so in practice because the shift in the lines is usually very small. In the example shown here, a star with a very large radial velocity has been chosen which shows a measurable Doppler shift on the enlargement.

There are numerous methods for determining the wavelengths of the shifted lines in this case. Probably the easiest way is to interpolate their wavelengths from the known wavelength positions of the iron lines. It should be a straightforward exercise to determine this using

Table 2: Wavelengths of lines in the spectrum of iron.

| Line | λ (nm) |
|------|----------------|
| A | 388.71 |
| B | 395.67 |
| C | 400.52 |
| D | 407.17 |
| E | 413.21 |
| F | 420.20 |
| G | 426.05 |
| H | 440.48 |

MaxIm DL. Once the shifted wavelengths are found, you will calculate the radial velocity of the star.