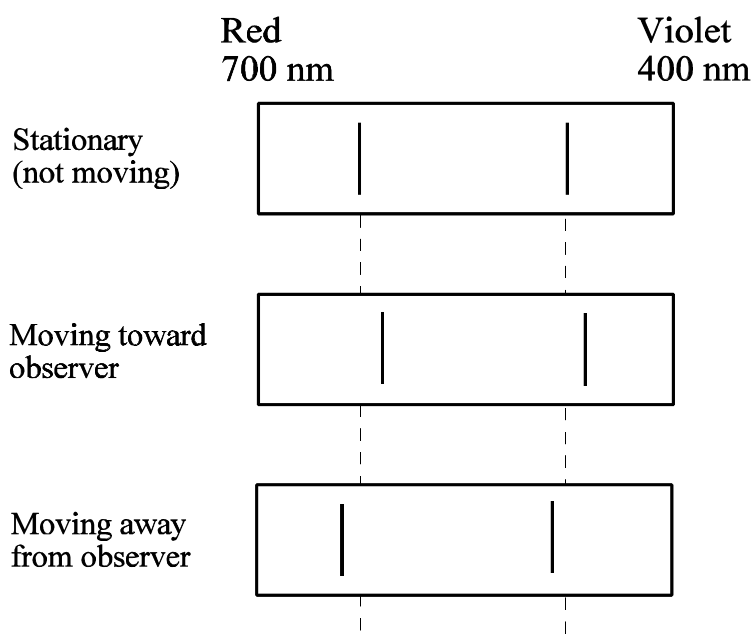
Name_____________________________ **Section**______________

Partner(s) _________________________ **Date**______________

SPECTROSCOPY IN MOTION: A WAY TO MEASURE VELOCITY

Did you ever hear a train whistle or truck on a highway as it approaches you and then passes at a high rate of speed? Describe the sound.

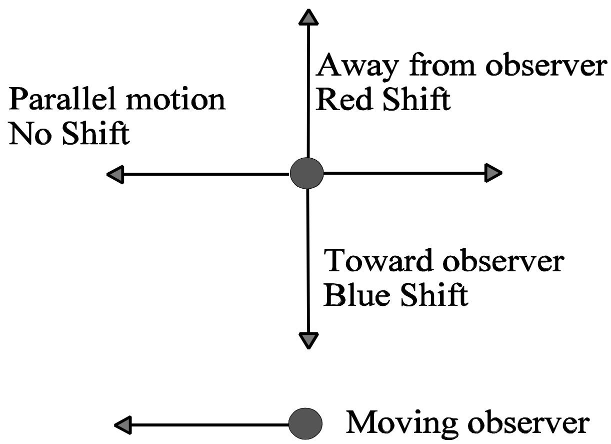
Now consider the stationary and moving spectra for visible light shown below:



How are the spectral lines, which are all produced by the same electron transitions in each spectrum, different for each spectrum?

Can you tell an approaching object from one moving away from you? Explain.

The difference in position of the lines for the moving spectra is due to the Doppler shift. The spectral lines of objects moving away from an observer are shifted toward the red end of the visible spectrum and are said to be red shifted; while objects moving toward an observer are said to be blue shifted. An object moving parallel with the observer would NOT see a Doppler shift in the spectrum, motion must be away from or toward the observer along the line of sight (line connecting observer with object).



Arrows show direction of motion

Using spectroscopy, the velocity (v) of the moving object can be determine from its red shift (or blue shift). The equation holds only if v << c or z < 1 (see below).

$$v \quad ' \quad (\frac{Äë}{ë})c$$

Where Äë is the shift in wavelength, ë, and c is the velocity of light. Red shifted objects will have a positive velocity, while blue shifted velocities will be negative.

Astronomers use the symbol z to represent the red shift or

$$z \quad ' \quad \frac{Äë}{ë}$$

How much of a shift, Äë, occurs for the each of the hydrogen spectral lines at 486 nm if z = 0.13 as measured for galaxies in Bootes? How about the line at 656 nm?

Redshift values of z = 4 have been measured for some distant quasars found at the edge of the universe. However, the velocity must be determined using the relativistic form of the equation when z >1.

Look at the table of information for a number of distant galaxies shown below.

Galaxy	Distance	Red Shift, z (Äë/ë)	Recession Velocity
Virgo	19 Mpc	0.00403	1,210 km/sec
Ursa Major	300	0.0500	15,000
Corona Borealis	430	0.0720	21,600
Bootes	770	0.1310	39,300
Hydra	1200	0.2040	61,200

What is their relative motion compared to the Earth? As distance increases, what happens to the red shift and recession velocity?

Plot a graph of recession velocity (v) on the y-axis vs. distance (d) on the x-axis. This plot illustrates Hubble's Law given by the equation:

$$v \ ' \ Hd$$

What type of relationship is found?

Determine the slope, change in recession velocity divided by change in distance, of the line. This is the Hubble constant, H. Make sure to include the units of the Hubble constant.

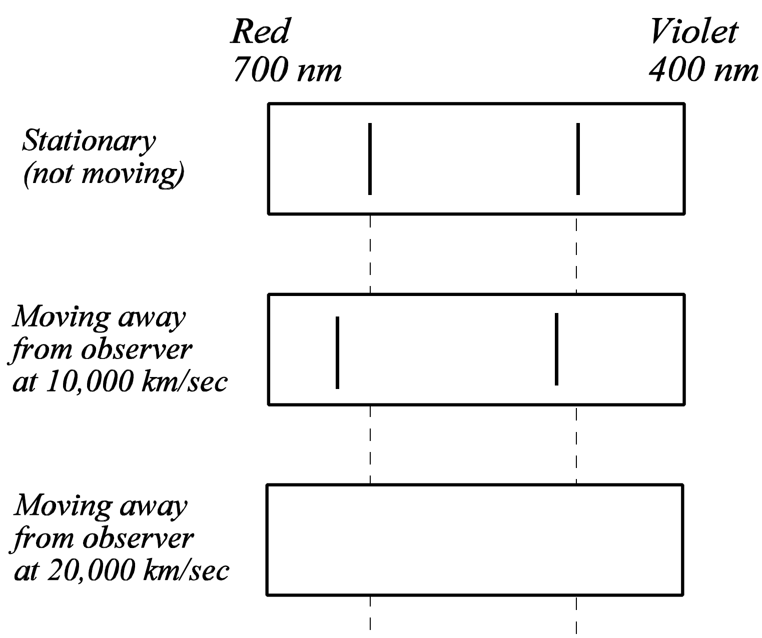
In 1936, Edwin Hubble first determined the value (H) for the relationship above to be 526 km/sec/Mpc. How does the modern value compare? On your graph, draw a line having a slope of 526 km/sec/Mpc, Hubble's original value.

The reciprocal of the Hubble constant is an estimate of the age of the universe. Find the age (in years), t_o, using the equation below and the various conversion factors.

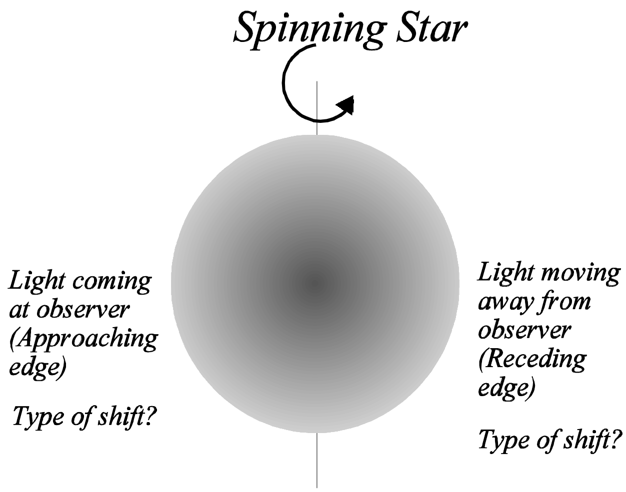
$$t_o = \frac{1}{H}$$

1 Mpc = 10^6pc   1 pc = 3×10^{13} km   1 yr = 3×10^7 sec

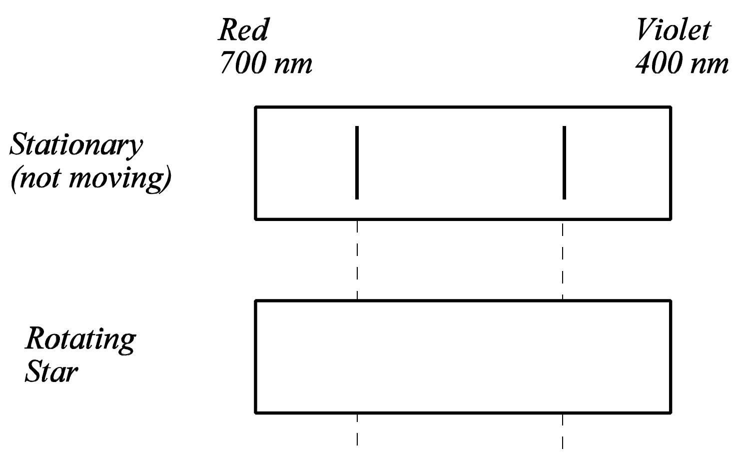
On the diagram carefully illustrate the spectrum for the object moving away at 20,000 km/sec.



Another practical application of the Doppler shift is for measuring the rotation velocity of stars. Extremely young B stars spin at their equator at 300 km/sec, while our Sun rotates at 2 km/sec.



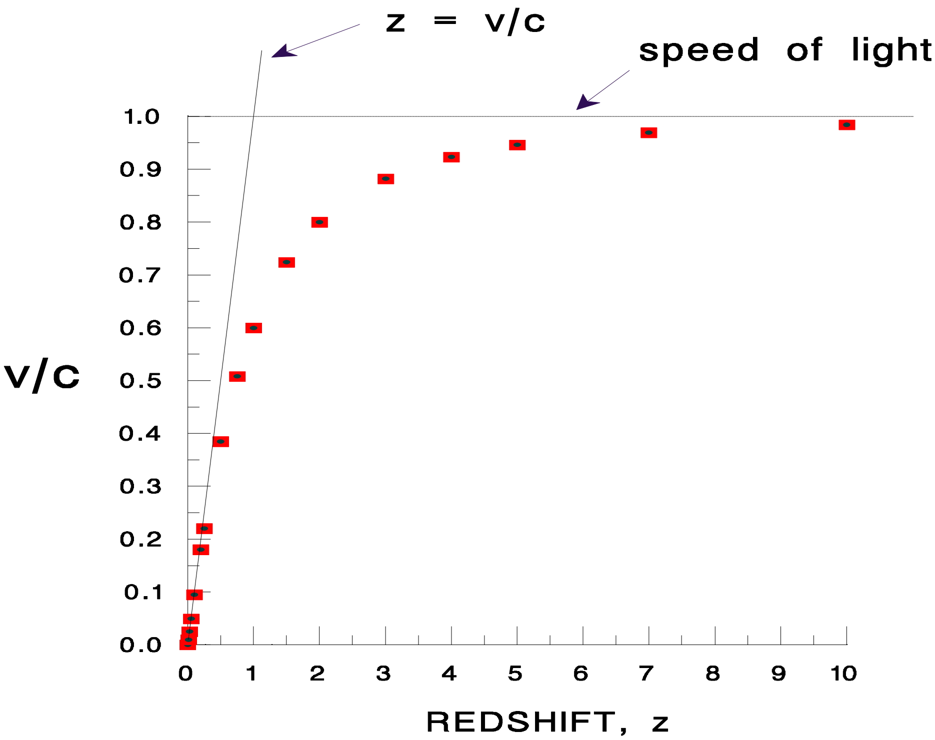
How do you think the spectral lines will appear in the rotating star's spectrum. Illustrate it on the diagram below.



If you were observing the star directly at its spin axis, would you see a Doppler shift? Explain.

The total width of a spectral line increases with increasing rotational velocity of a star.

Nothing can go faster than the speed of light (c), 3.0 x 10^5 km/sec. This is the cosmic speed limit! Consider the plot of redshift, z, against v/c ratio, where the ratio is corrected for relativistic effects.



The earlier equation, z = v/c is shown on the graph above. How well does the data agree with the equation?

The data points fall on this line when z < 1. However, as z > 1 the data points are considerably away from the z = v/c line. The data points curve to approach the cosmic speed limit, the speed of light.

Using special relativity developed by Einstein, the relativistic version of the equation relating redshift to velocity is given by:

$$z = \sqrt{\frac{1+v/c}{1-v/c}} - 1$$

This equation above simplifies to the nonrelativistic form, z = v/c, when v << c.

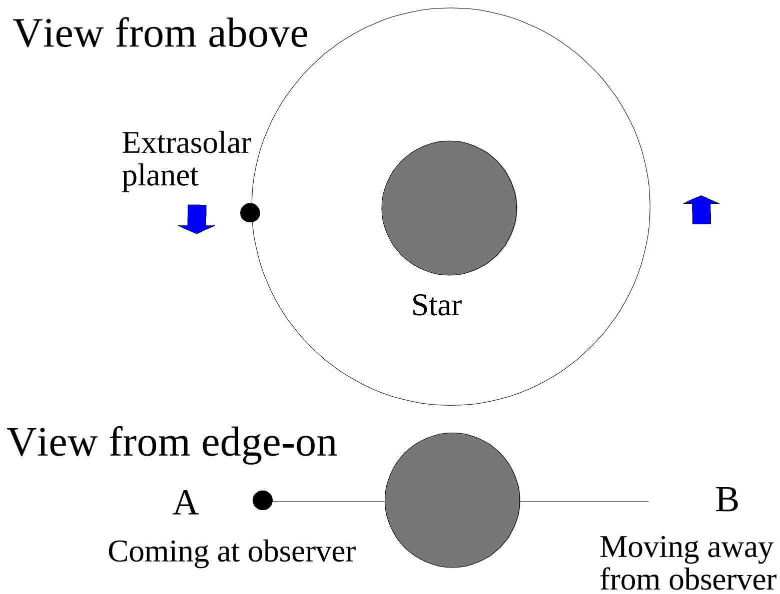
The largest redshift measured for the galaxy RD1 is 5.34 (*Science*, 13 March 1998). Determine the v/c ratio for RD1 by either using the relativistic equation above **OR** estimate from the graph above.

The RD1 galaxy has a velocity of 0.95c. If the 122 nm hydrogen line, which is considered in the far ultraviolet, was detected in RD1, what would its Äë be? What part of the electromagnetic spectrum would the line appear in after the shift? Some common wavelength regions and their wavelengths are given in the table below. Remember that z = Äë/ë.

Region	Wavelength (nm)
Ultraviolet	10 - 400
Visible	400 - 700
Infrared	700 - 100,000

The discovery of extrasolar planets has been aided due to recent advances in spectrometers with very high resolutions able to measure extremely small wavelength shifts. From the variation in a star's Doppler shift caused by an orbiting planet, the period of the planet, its orbital radius and velocity, and minimum mass can be determined. Most spectrometers in use for searching for extrasolar planets claim a detection down to 10 m/s. In nanometers, this is an incredibly small shift, but it can be done!

Consider an extrasolar planet orbiting a star. The mass of the extrasolar planet causes a wobble in the star that can be determined by the Doppler shift variation measured over time using very sensitive spectrometers. The star and extrasolar planet are moving away from the observer and the system would have a red shift. However, since the system wobbles, due to the planet causing the center of mass of the system to be off set from the center of the star, the velocity curve shows a cyclic variation.



Center of mass check:

1. Balance a meter stick on the tip of your finger. Where is the balancing point (what distance)?

2. Now place a 200 g mass on the zero end of the meter stick and a 20 g mass on the 100 cm end. Where is the balancing point?

3. The balancing point is the center of mass for each case above. The system would rotate around the center of mass. Does this make sense that this would make the star or more massive object appear to be wobbling?

For the Sun and its most massive planet, Jupiter, the wobble in the Sun is about 12 m/s. On the view from edge-on above, the star is slightly blue shifted, when the extrasolar planet is at A or B? (Hint: think about the star's motion!) Explain.

Plot a graph of the radial velocity against time for a possible extrasolar planet orbiting a star.

Time (days)	Radial Velocity (m/s)
1	117.8
2	127.3
3	19.8
4	-106.0
5	-134.2
6	-39.1
7	92.0
8	138.5
9	57.7
10	-76.2

How would you describe the nature of the data on the graph?

How would you determine the time of one full cycle or revolution of the extrasolar planet? First label points A and B from the above diagram on your graph.

From the plot determine the period of the extrasolar planet.

The cyclic variation is a sine function for extrasolar planets with a circular orbit (eccentricity, e = 0). The following stars have extrasolar planets in circular orbits:

51 Pegasi B, 47 Ursae Majoris B, ô Bootes B, and Upsilon Andromedae B

Information on recent discoveries can be found on the Extrasolar Planet Encyclopedia (http:// wwwusr.obspm.fr/planets).