The Hubble Law*

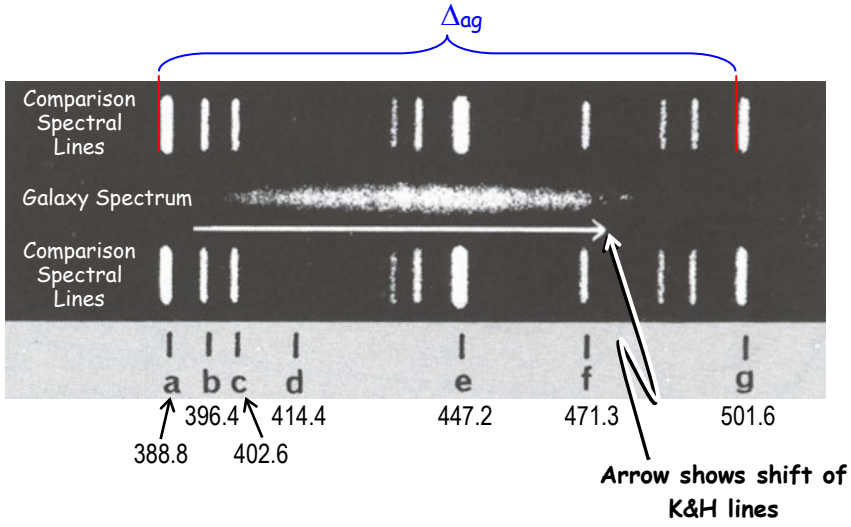
The prominent spectral lines of galaxies are redshifted due to the Doppler effect, produced by an object receding from the observer. This was described by Edwin Hubble as the *Hubble Law*,

$$v = H_o d$$

where **v** is the recessional velocity of the galaxy (in kilometers per second), **d** is its distance and $\mathbf{H_o}$ is the Hubble Constant. $\mathbf{H_o}$ is a measure of how rapidly the Universe is expanding.

Scaling Factors

In the photos on p. 4 and the one to the right, the galaxy's spectrum is the blur in the middle with comparison spectra above and below showing lines of known wavelengths. The spectra of the galaxies each show two prominent dark lines, the K and H lines of ionized calcium at λ_K = 393.4 nm and λ_H = 396.9 nm. The arrow represents the amount by which the K and H lines have been redshifted using the wavelength between them, λ_{KH} = 395.1 nm.



★ Measure the distance (in mm) between two <u>widely spaced</u> lines (such as **a** and **g**).

★ From the diagram above, find the wavelengths for the comparison lines used, λ_{left} and λ_{right}.

★ Calculate the wavelength scale by finding the ratio of $\lambda_{right} - \lambda_{left}$ to distance **D**.[5]

Distance: $D_{a\ to\ g}$ = _____ **mm**, Wavelengths: λ_{left} = _____ nm, λ_{right} = _____

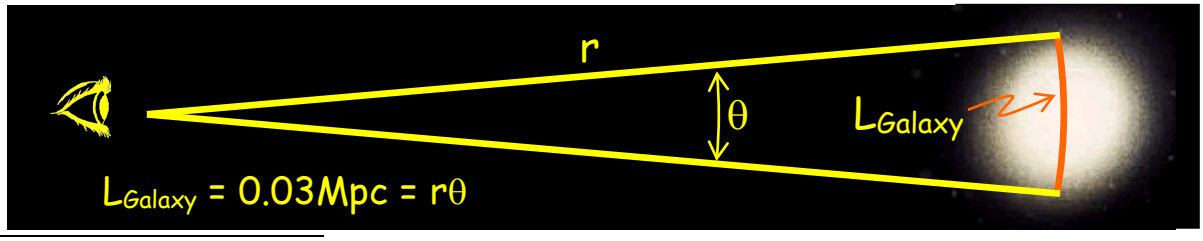
$$\text{Wavelength Scale} = \frac{\lambda_{right} - \lambda_{left}}{D_{a\ to\ g}} = \_\_\_\_\_\ \frac{nm}{mm}$$

★ Measure the length (in mm) of the 150" line at the bottom of the page.

★ Calculate the size scale by finding the ratio of the angular size to measured size[3]

Length of 150" Line: $L_{150"}$ = _____ **mm**

$$\text{Size Scale} = \frac{150"}{L_{150"}} = \_\_\_\_\_\ \frac{arcsec}{mm}$$



* After Evans, A., "Laboratory Exercises in Astronomy – Hubble's Law" *Sky & Telescope* April 1978

Recessional Velocities

For each spectrum on the diagram,[20]

★ Measure the length of the arrow in **millimeters** showing the shift of the K & H lines.

★ Convert the measured shift to wavelength shift by using your scale:

$$\Delta\lambda_{K\&H} = \left(L_{Arrow}\right)\left(\text{Wavelength Scale}\right)$$

★ Find the recessional velocity of the galaxy by use of the equation to the right where c is the speed of light, c = 3.0 x 10^5 km/s.

$$v = \frac{\Delta\lambda_{Galaxy}}{\lambda_{KH}}c$$

Galaxy	Length of Arrow mm	Wavelength Shift $\Delta\lambda = (L_{arrow})\times(W.S.)$ nm	Recessional Velocity $(\Delta\lambda/\lambda_{KH})\times c$ km/sec
Virgo			
Ursa Major			
Corona Borealis			
Boötes			
Hydra			

Galaxy Distances

Assume all the galaxies are the same size so their apparent sizes are proportional to their distances[30]

★ Measure the width of each galaxy in millimeters.

★ Convert the size to angular width by using your scale: $L_{arcsec} = L_{mm}\left(\text{Size Scale}\right)$

★ Convert the arcseconds to radians using the fact that 206,265″ = 1 radian

★ Convert to distance assuming L_{galaxy} = 0.03 Mpc and

$$r_{galaxy} = \frac{0.03Mpc}{L_{radians}}$$

Galaxy	L_{max} mm	L_{min} mm	$\langle L_{mm}\rangle = (L_{min}+L_{max})/2$ mm	$L_{arcsec} = \langle L_{mm}\rangle(SS)$ arcsec	$L_{radians} = L_{arcsec}/206{,}265$ radians	Distance $=0.03Mpc/L_{radians}$ Mpc
Virgo						
Ursa Major						
Corona Borealis						
Boötes						
Hydra						

Calculating the Hubble Constant:

Use Excel to plot data for your galaxies

★ Open T:\astronomy\Hubble and save it to your own One Drive

★ **Type your values into the white boxes**

★ Don't type on colored boxes!!

★ Calculations will be made as you type.

★ Your Hubble plot will appear at the bottom

★ **The equation for your line will appear on the plot with numbers instead of ##.**

$$y = \#\#x - \#\#$$

★ **The coefficient of x is the slope which is your value of H_0**, write it here and type it into the bottom white box[20]

$$H_0 = \_\_\_\_\_ \frac{km/s}{Mpc}$$

The current value of H_0 is about 72 km/s/Mpc. **How does your value compare?**

Calculation & Plotting of the Hubble Constant (S&T Exercise)

Find the Wavelength Scale

λ_{span} (a-g) 112.8 nm

$D_{a\ to\ g}$ mm

#DIV/0! nm/mm = W.S.

These are your measurements from the front page.

Find the Size Scale

angle 150 arcsec

$L_{150"}$ mm

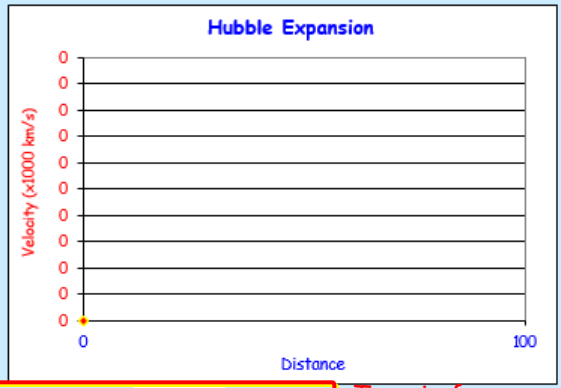
#DIV/0! asec/mm = S.S.

$\lambda_{O,\,KH}$ = 395.1 and $\lambda_{observed} = \lambda_{O,\,KH} + \Delta\lambda$

c = 3.00E+05 km/s

	Arrow	Δλ	$\lambda_{observed}$	Speed
	L	L*(λ/D)	L_O + Shift	(Shift/L_O)*c
	mm	nm	nm	km/s
Virgo		#DIV/0!	#DIV/0!	#DIV/0!
Ursa Major		#DIV/0!	#DIV/0!	#DIV/0!
Corona Borealis		#DIV/0!	#DIV/0!	#DIV/0!
Boötes		#DIV/0!	#DIV/0!	#DIV/0!
Hydra		#DIV/0!	#DIV/0!	#DIV/0!

	Galaxy Size					Distance
	Maj Axis	Min Axis	Average	Angle on sky		
	mm	mm	mm	arcsec	radians	Mpc
Virgo			0	#DIV/0!	#DIV/0!	#DIV/0!
Ursa Major			0	#DIV/0!	#DIV/0!	#DIV/0!
Corona Borealis			0	#DIV/0!	#DIV/0!	#DIV/0!
Boötes			0	#DIV/0!	#DIV/0!	#DIV/0!
Hydra			0	#DIV/0!	#DIV/0!	#DIV/0!



H_0 from plot = km/s/Mpc Type in from equation on plot

Hubble Time = #DIV/0! years = #### billion yr

Your age of the universe.

The Hubble Time

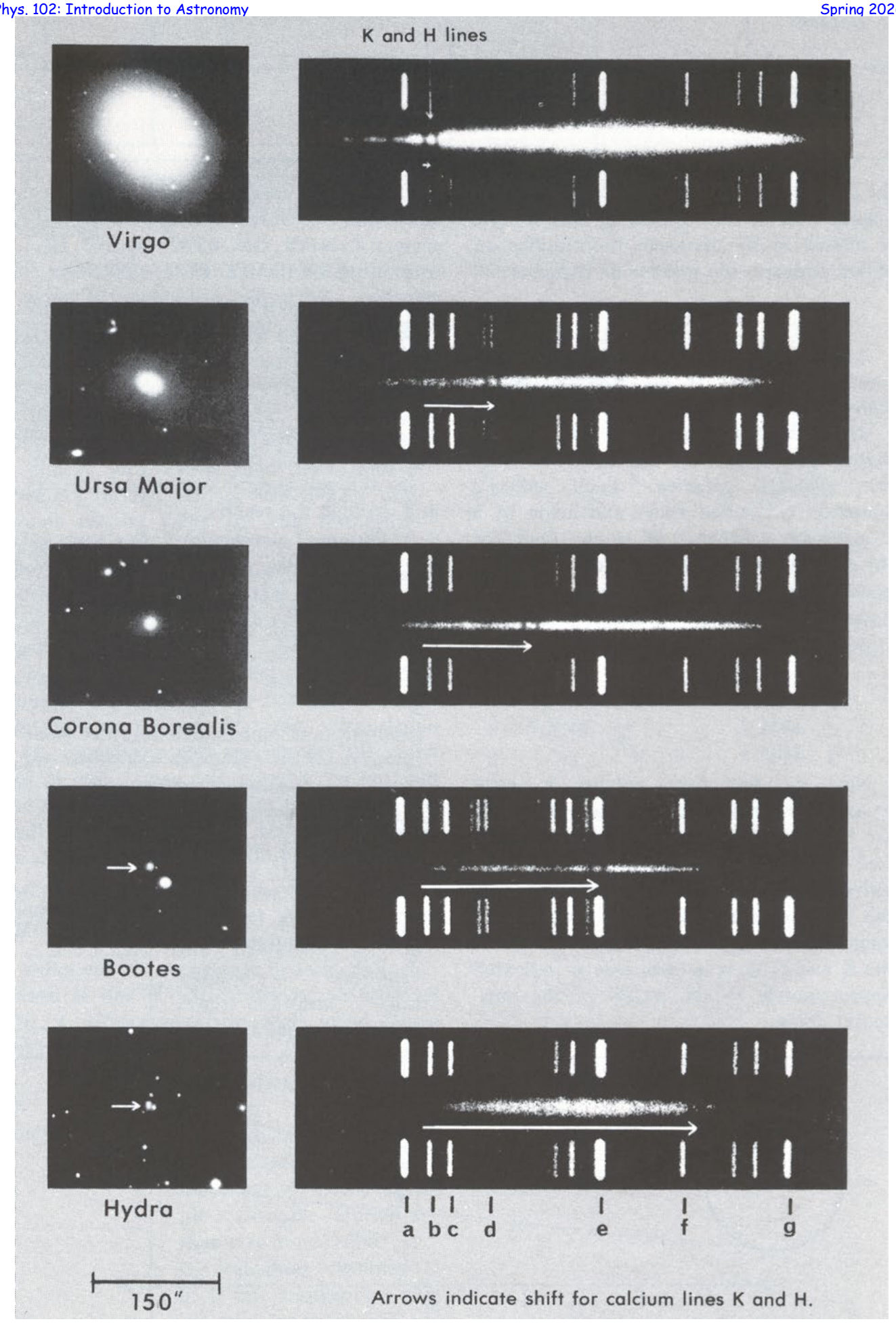
The age of the Universe is approximately the inverse of the Hubble constant; $1/H_0$. But we must convert the units. For your H_0, the time will be calculated using 1 Mpc = 3.09 x 10^{19} km and 1 yr = 3.1536 x 10^7 sec. **Write your value below and comment on it. How could you improve your measurements?**

$$t_{Hubble} = \frac{1}{H_o\left(\frac{km}{Mpc \cdot sec}\right)}\left(\frac{3.09 \times 10^{19} km}{1\ Mpc}\right)\left(\frac{1\ yr}{3.1536 \times 10^{7}\ sec}\right) = \frac{9.798 \times 10^{11}}{H_o} years$$

Age of The Universe = _____ years

How does this compare to the currently accepted 13.8 Billion year age of the universe?

Print out a copy of your spreadsheet page and attach it … print to SLU_Public_Printing_color.


K and H lines
Virgo
Ursa Major
Corona Borealis
Bootes
Hydra
a b c d e f g
150"
Arrows indicate shift for calcium lines K and H.