Student's name______________________________

AstroParticle Physics 2007/08 (De Angelis)

Laboratory 1
Hubble's law and the expansion of the Universe

1. Purpose

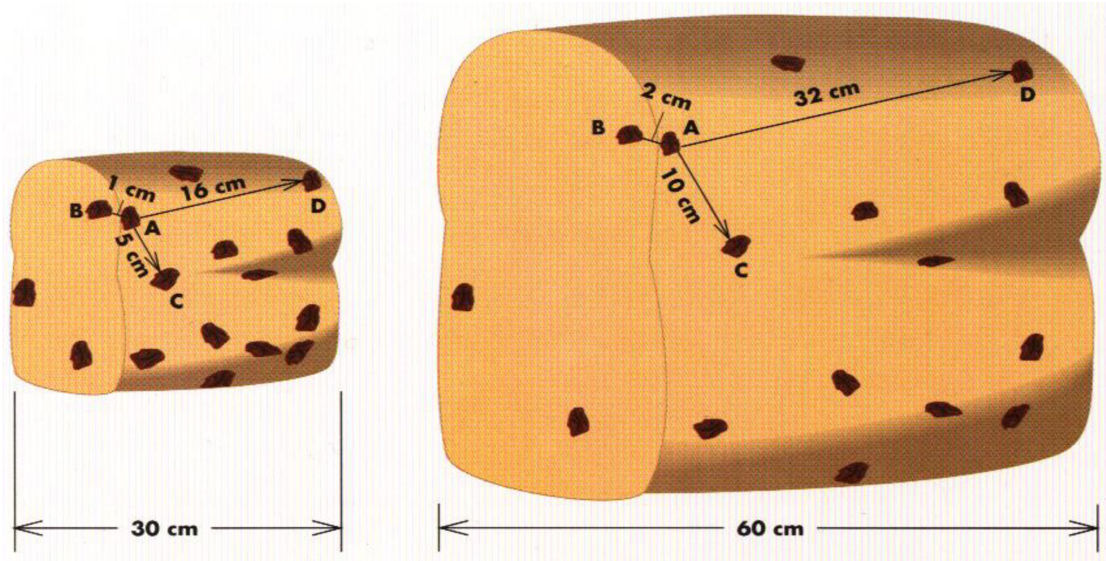
The purpose of this laboratory exercise [1] is to study galactic recession and the famous relationship between velocity and distance found by Edwin Hubble in 1929 [2]:

$$V = H_0\ r \qquad (1)$$

where V is the recession velocity (in km/s), r is the distance (in Mpc; 1 pc ~ 3.3 light years), and H_0 is Hubble's constant (in km/s/Mpc, or just s^{-1}). According to Time this is the most important discovery of the second millennium!

Hubble's law means that every point is receding from any other point: the space itself is expanding. As a model, you can think to a plumcake growing in an oven (Figure 2 on the following page).

This laboratory will introduce several methods used to determine the Hubble constant, but will concentrate on the method originary proposed by Hubble.



2. Introduction

The precise determination of the distance to galactic objects is not easy. Methods that we commonly employ every day are of little use over such large distances; even the method of parallax using the Earth's orbit is of little help for such large distances as those between galaxies. Distances to some of the nearest galaxies are uncertain by ten percent, while distances to some of the most visible clusters are uncertain by a factor of two at least. It should not be surprising that the further away an object is, the less accurately its distance can be measured.

The methods by which we are able to measure galactic distances are indirect and to a large extent are dependent on the properties of the brighter stars contained in galaxies. In order to make any use of these bright objects, we must assume that the objects in nearby and distant galaxies are basically the same or at least very similar to objects in our own galaxy. By assuming this we can make use of several events in neighboring galaxies.

Similarly, estimates have been made by observing the brightest stars in galaxies and assuming that they are comparable in magnitude to stars in nearby galaxies of a similar type. However, these values are also uncertain.

We can also use the maximum magnitude of supernovae to estimate galactic distances. This has become very popular in the last years, since the Supernova Cosmology Project claimed violations in the Hubble's law [3] which are consistent with an acceleration in the expansion of the Universe. However, these events do not occur frequently and hence are not available for systematic and intensive study; a satellite (SNAP, [4]) is under project for a dramatic increase in the statistics.

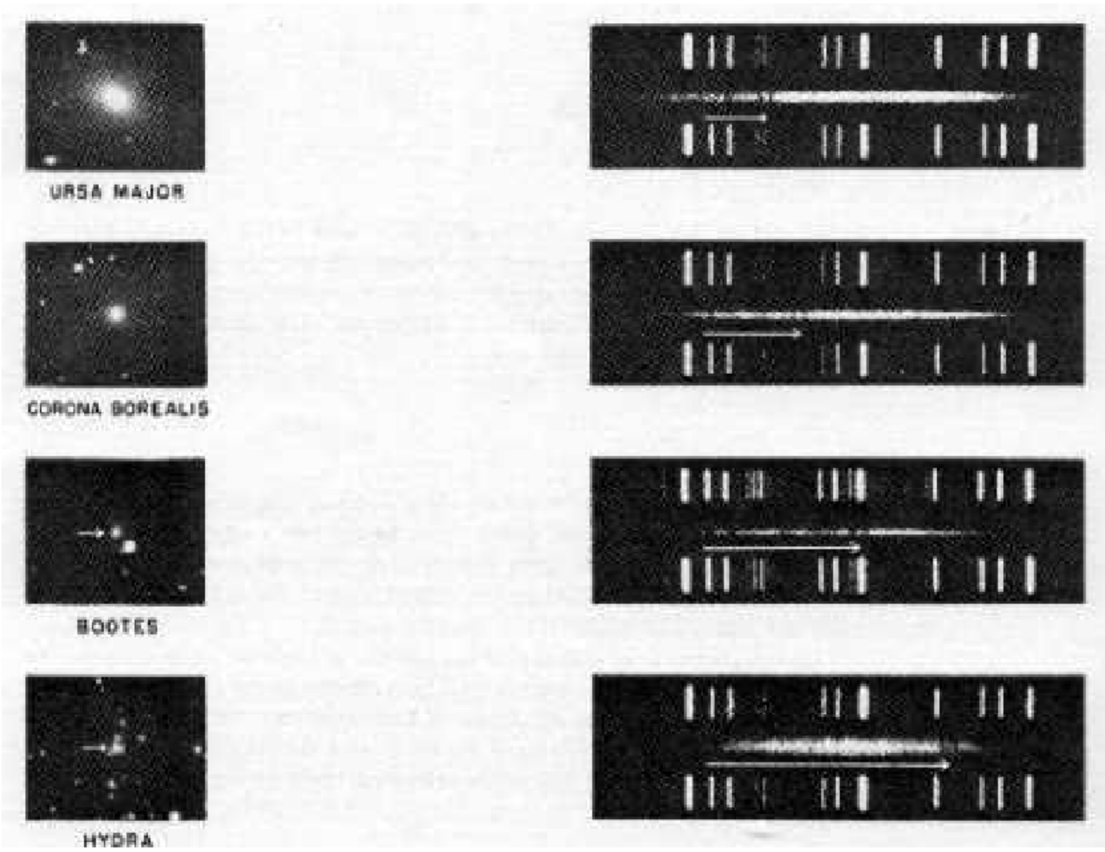
3. Procedure

Once one has established a “standard candle”, one can derive its distance from its luminosity (luminosity decreases as the square of the distance).

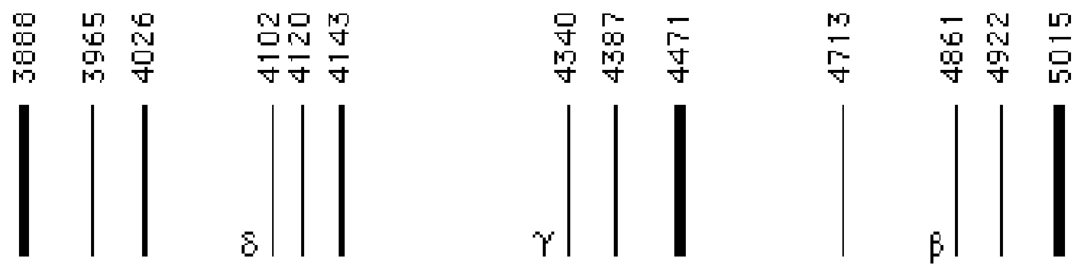
3.1 Determination of the velocity

Velocity can be derived from the so-called “red shift”: because of the Doppler effect, if a source moves away with a speed V, its wavelength is moved towards the red (see Eq. (2) below). Think to the sound of an ambulance: if the ambulance moves away, the apparent frequency of the siren sound is lower.

The Figure 3 below gives the spectra of Hydrogen for four clusters of galaxies.



A comparison spectrum for hydrogen identifying the various lines is given in the subsequent Figure 4.



Determine the red shifts and velocities of recession for the four clusters in Figure 3 following the steps described below.

I. Calculate the range of values for wavelength in Figure 4. Next measure the distance in centimeters of a pattern in Figure 3. Determine the scaling factor for the spectra of Figure 3 by dividing the range of wavelength values in Figure 4 by the corresponding distance in centimeters of a pattern in Figure 3.

Wavelength range of spectra in angstroms _______Å .

Measured range of a spectra _______ cm.

Scaling factor _______ Å / cm

II. Now measure the red shift. The red shift is denoted in the spectra in Figure 3 by the arrow. First measure the red shift in centimeters; then using your scaling factor convert it to wavelength.

(Cluster)	Δl (cm)	$\Delta\lambda$ (Å)
Ursa Major	_______	_______
Corona Borealis	_______	_______
Bootes	_______	_______
Hydra	_______	_______

IV. The Doppler equation can be used to determine the velocity V of the cluster once its red shift is known

$$1+\frac{\Delta\lambda}{\lambda}=\sqrt{\frac{1+V/c}{1-V/c}} \qquad (2)$$

where c = speed of light = 3.0 x 10^5 km/s; λ = 3933 Å (unshifted wavelength). You can demonstrate that, for V/c << 1,

$$\sqrt{\frac{1+V/c}{1-V/c}} \cong 1+V/c$$

Now calculate the velocity of each cluster.

(Cluster)	V (km/s)
Ursa Major	________
Corona Borealis	________
Bootes	________
Hydra	________

3.2 Relationship between velocity and distance

With the procedure described above, one can determine the following table

	Distance (Mpc)	Velocity (km/s)
Pegasus	57	3810
	69	3860
Perseus	80	5430
	120	4960
Coma	87	6657
	180	7200
Hercules	158	10400
	218	12800
Gemini	450	23400
	552	22400
Leo	460	19200
Ursa Major 2	685	40400
	830	40000

I. Plot Velocity versus Distance in a linear scale; comment. As an example, below you can see a copy of the original plot by Hubble [2].

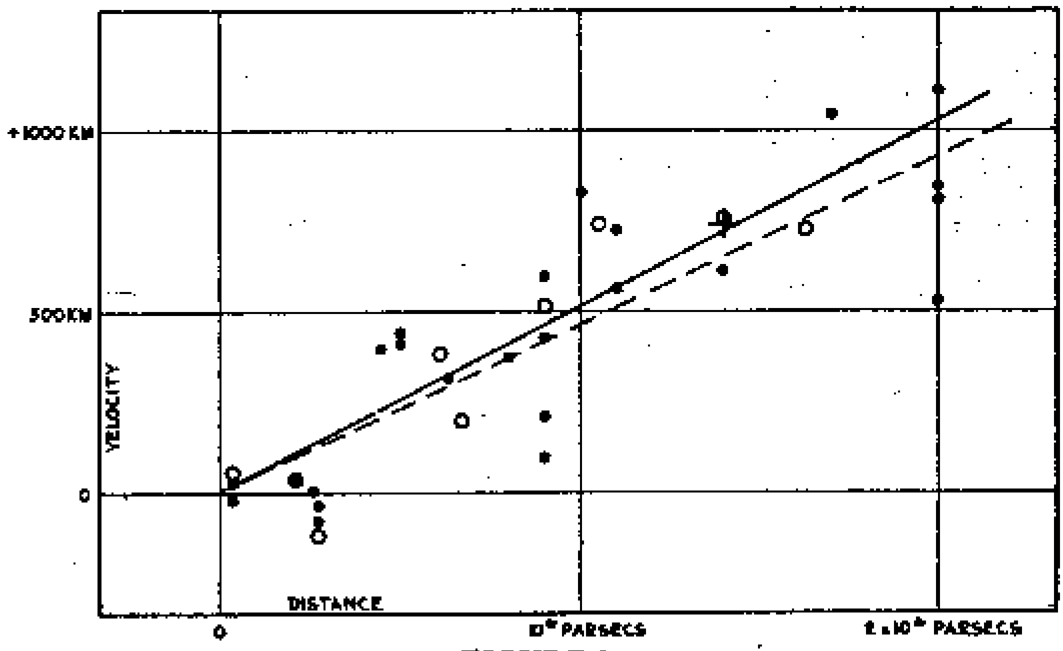


FIGURE 1

II. Fit the table to expression (1), obtaining the best value of the Hubble's constant. Assuming that the uncertainty on V/D is constant and that the typical error on H_0 is

$$\sigma_{H_0} \approx \sqrt{\frac{\sum_i (V_i/D_i - H_0)^2}{N-1}}$$

a. Calculate the value of the Hubble Constant with its uncertainty

H_0 = ____________ $\pm$ ______________ km/s/Mpc

Comment, comparing to the currently accepted value of 71^{+4}_{-3} km/s/Mpc [5].

Can you observe the violations from linearity claimed in [3] ?

b. Estimate the age of the Universe, in years (in a first approximation, imagine that the recession velocity was always H_0).

T = ____________ $\pm$ ______________ y

References

[1] http://campus.houghton.edu/webs/employees/myuly/Courses/esci102/
[2] E. Hubble, Proc. Nat. Academy of Sciences 15 (1929) N. 3.
http://cfa-www.harvard.edu/~lli/personal/images/science/hub_1929.html
[3] S. Perlmutter et al., Ap. J. 517 (1999) 565.
[4] http://snap.lbl.gov/
[5] http://lambda.gsfc.nasa.gov/product/map/wmap_parameters.cfm