HUBBLE'S LAW

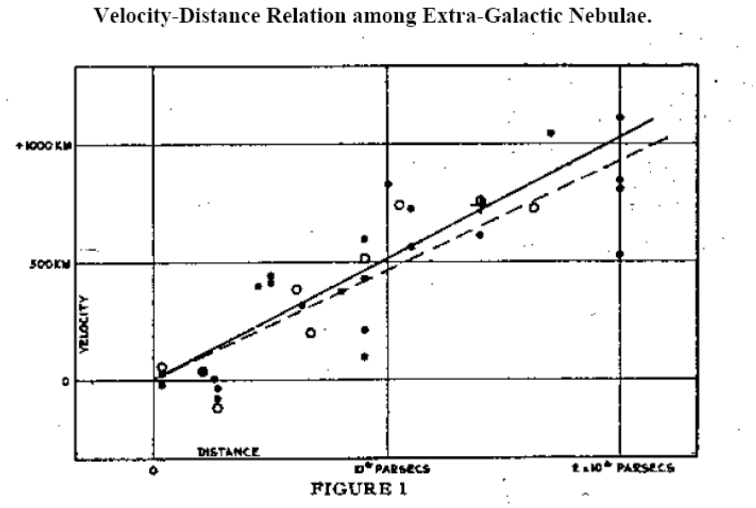

Figure 1. Velocity–distance relation among extragalactic nebulae. The caption, as written in Hubble's famous paper of 1929 reads: "Radial velocities, corrected for solar motion, are plotted against distances estimated from involved stars and mean luminosities of nebulae in a cluster. The black discs and full line represent the solution for solar motion using the nebulae individually; the circles and broken line represent the solution combining the nebulae into groups; the cross represents the mean velocity corresponding to the mean distance of 22 nebulae whose distances could not be estimated individually". (Note: Velocity units should be in km s^{-1}.) [Hubble E (1929) A relation between distance and radial velocity among extra- galactic nebulae. *Proc. Natl. Acad. Science USA* **15**(3):168–173.]

CCEA GCE Physics
Unit AS 2: 2.7 Astronomy

Objective

To use galaxy red shifts to measure the expansion rate of the Universe and determine the value of the Hubble constant. You will use images and spectra of real galaxies to measure the angular size of galaxies and so derive their distance. You will also measure the redshift of each galaxy and hence the speed it is moving away from us.

Background & Theory

In 1929, Edwin Hubble discovered a relationship between a galaxy's distance from us and how fast it is moving away from us (i.e. its recessional velocity). This relationship, now known as Hubble's Law[1], states that the recessional velocity of a galaxy is proportional to its distance from us: $\boldsymbol{v = H_0 D}$.

Here $\boldsymbol{v}$ is the galaxy's velocity in units of km s^{-1}, $\boldsymbol{D}$ is the distance to the galaxy in units of megaparsecs (Mpc; 1 Mpc = 1 million parsecs), and $\boldsymbol{H_0}$ is called the Hubble Constant.

For example, Hubble's Law states that a galaxy moving away from us twice as fast as another galaxy will be twice as far away from us as the other galaxy. Accurately measuring the value of $\boldsymbol{H_0}$ was a key science project of the Hubble Space Telescope.

Figure 1 shows a reproduction of the first published Hubble diagram. In his original work, Hubble was only able to measure velocities and distances of a few nearby galaxies, and so his original estimate of the Hubble Constant is different from the modern day value. But Hubble was able to correctly show that the Universe is expanding.

[1] Strictly, it should be known as the Hubble-Lemaître Law – see your lectures notes and the Astronotes blog.

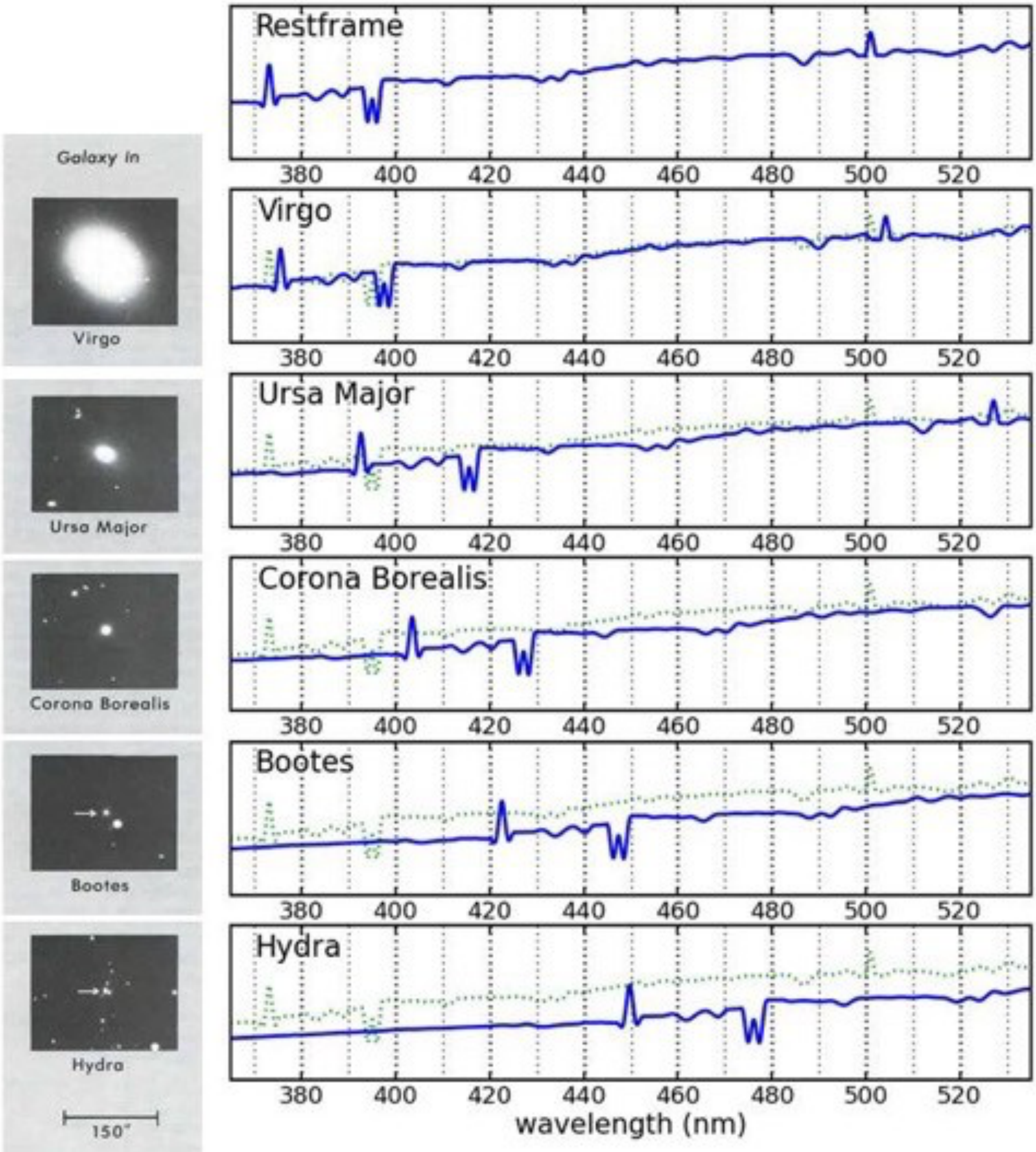

Figure 2 contains images (on the left) and spectra (on the right) for five galaxies. For each galaxy you will determine its *distance* and recessional *velocity*. We make the simplifying assumption that each galaxy has the same physical size. Hubble managed to directly measure the distance to the largest galaxy here (Virgo) by identifying a special kind of star in it whose absolute brightness can be measured in our own Galaxy. The image size of the galaxy will then be inversely proportional to its *distance*. So, by measuring their relative image sizes we can infer how far away each galaxy is. The *velocity* of each galaxy can be determined by measuring its redshift using the wavelength of the spectral lines seen in each galaxy and comparing them to their rest wavelength. In this particular case we will use the two prominent absorption lines seen in the spectrum, which are produced by the element calcium.

Step 1 – Determining the Distance

1. Measure the diameter, ***d***, in millimetres (mm) of all 5 galaxies. Make your measurements as accurately as possible, preferably within 0.2 mm. For galaxies that are not circular in shape, determine the diameter along the longest and shortest dimensions and average the two values. The fifth galaxy is a double galaxy, only measure the galaxy on the left, indicated by the arrow. Record the diameters of each galaxy in the data table.
2. All of the galaxies you have measured are "giant elliptical" galaxies. Hubble used these kinds of galaxies because they have smooth, regular shapes that are easy to measure. Astronomers know that, on average, all giant elliptical galaxies have about the same size. The galaxies you have measured have different image sizes because they are at different distances from us. Those furthest away have the smallest measured image diameters.

   We will assume that the distance to the Virgo galaxy is 32 Mpc (mega-parsecs). Hence determine the distance to each galaxy by assuming that distance, ***D*** is, inversely proportional to image diameter, ***d***. i.e.

   $$D = 32\, d_{virgo} / d \text{ Mpc},$$

   where d_{virgo} is the diameter (in mm) of the galaxy in Virgo.

Step 2 – Determining the Velocity

The right side of Figure 2 is the observed spectrum of each galaxy. The wavelength scale is shown at the bottom of each spectrum. Note the two dips of the absorption lines. These are produced by the element calcium. These lines appear near 395nm in the "rest frame" spectrum at the top of the Figure.

1. Measure the wavelength of the calcium absorption lines in nanometres (nm) for each galaxy. Record these values (in nm) in your data table.
2. Use the Doppler redshift equation [$z = (\lambda - \lambda_0) / \lambda_0$] to calculate the redshift (***z***) of each galaxy. The average rest wavelength of the calcium lines (λ_0) is 395nm. Record these values in your data table.
3. Calculate the recessional velocity of each galaxy in km s^{-1} and record these values. The velocity is just the redshift multiplied by the speed of light (***c***) in km s^{-1}, where ***c*** = 300,000 km/s, and is given by: $v = c\, z$.
4. Using the graph provided, make a plot of the recessional velocity (in km s^{-1}) of the galaxies versus their distance (in Mpc). Velocity should be on the vertical axis and distance on the horizontal axis. Be sure to label your axes.
5. What do you see? Is there a linear relationship between the two quantities? Draw the best fitting straight line to the data. The line does not need to go through all the data points, but should be represent the average trend of the data.

Part 3 – Determining Hubble's Constant

1. How might you determine Hubble's constant from this graph? Hint: what are the units of the slope of the best fit straight line?

2. Determine the slope of your best-fit line. This can be found by picking two points on your graph that the line goes straight through (they do not have to be data points). From these, read the y-values (velocity) and the x-values (distance). Divide the difference in velocities by the difference in distances to get the slope of your line. This will be in units of (km s^{-1}) / Mpc. This is your estimate of the Hubble Constant, $\boldsymbol{H_0}$.

3. Discussion question: how might measurement errors affect your determination of $\boldsymbol{H_0}$?

Galaxy Name	Measured Diameter *d* (in mm)	Distance *D* (in Mpc)	Wavelength (in nm)	z (redshift)	Velocity (in km/sec)
		$D = 32\, d_{Virgo} / d$ Mpc		$z = (\lambda - \lambda_0)/\lambda_0$: λ_0 = 395 nm	$v = c\, z$: c = 300,000 km s^{-1}
Virgo		32			
Ursa Major					
Corona Borealis					
Bootes					
Hydra