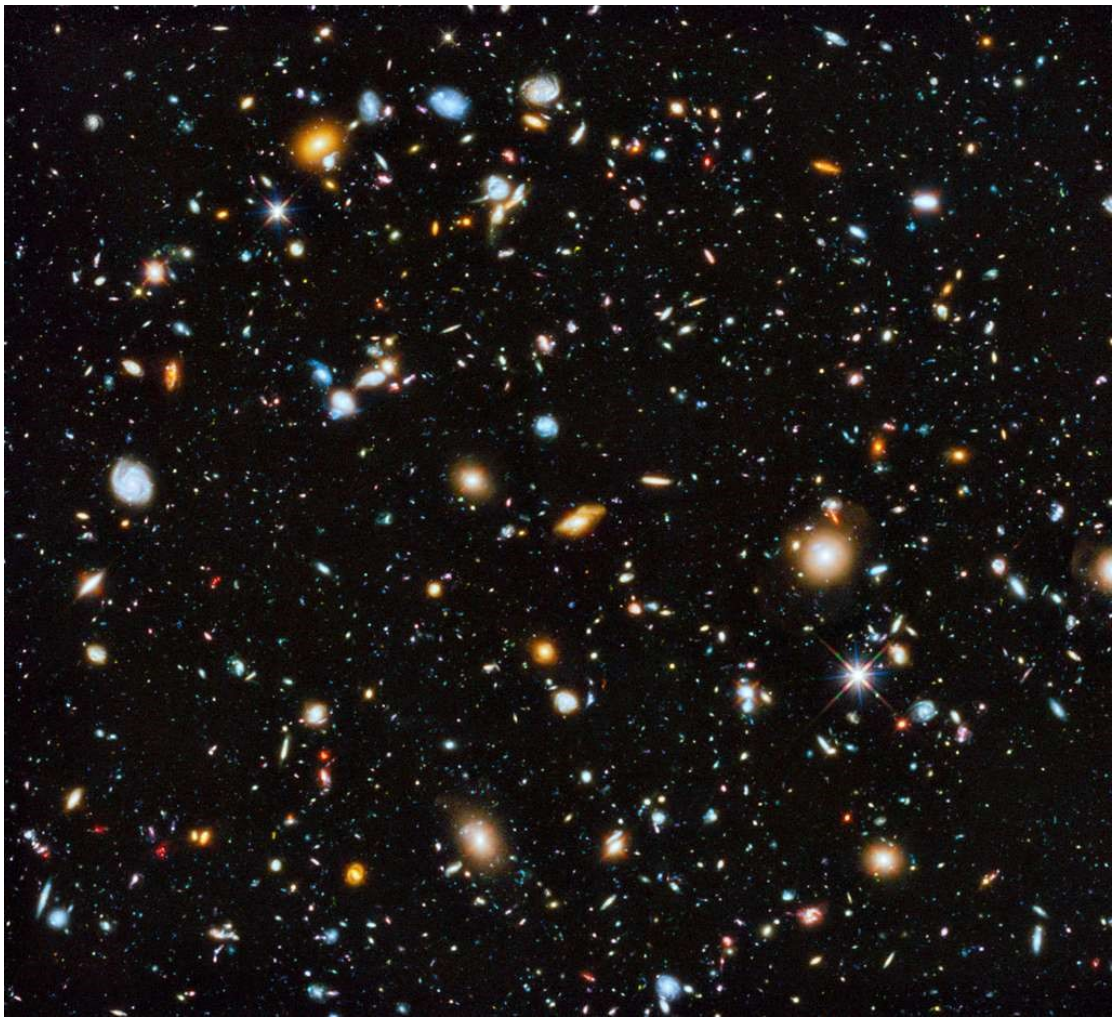
“Measuring the recess velocity of distant galaxies”: calculating the age of the Universe

FRONTIERS

PCCP demonstrator



Orienting and Asking Questions

Provide Contact with the content and/or provoke curiosity

Hubble and the galaxies:
In the ‘20s, Edwin Hubble observed the sky from Mount Wilson Observatory, county of Los Angeles, California. The most powerful telescope at the time, the Hooker telescope with a diameter of 250 cm, had just being installed there.
Thanks to the Hooker telescope, Hubble was able to measure the distance of a number of nebulae, exploiting the properties of a type of stars called Cepheids. These stars have the characteristic of twinkling: their luminosity has a periodic variability. The more luminous the star, the faster the luminosity changes. Using this property, Hubble was able for the first time to measure the distance of the nebulae containing this type of stars.
The distances he obtained are larger than any other previously measured: he unveiled the existence of other galaxies outside our own, the nearest to us being Andromeda, a mere two million light-years away. Before then, it was believed that our Milky Way represented the entire Universe. From that point on, every new distance measurement pushed the limits of our Universe further and further away.

Figure 1: Edwin Hubble at the Mount Wilson Observatory (Image: © Mt. Wilson Archive, Carnegie Institution of Washington).

Spectral lines and how to use them:
Not long before the observations by Hubble, Vesto Slipher had studied the light spectra of some astronomical objects that he didn't yet know to be galaxies: when observing an astronomical object, we can decompose its light, which might at first appear as white or whitish, in a rainbow of colours. It is this "rainbow" that we call spectrum. The interesting characteristic of this decomposition is that in the spectrum of astronomical objects we find some black bands, called absorption lines. The specific place in the spectrum of such absorption lines (what is called their wavelength) depends on the chemical composition of the observed object.
Vesto Slipher used well-known reference spectra to show that the absorption lines of what we now call spiral galaxies (like the Milky Way or Andromeda) were shifted towards the red, hence longer wavelengths, with respect to the reference. Assuming that the red-shift was due to the Doppler effect, Slipher concluded that the observed objects are recessing from us.

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If your students are not familiar with spectral lines and the Doppler effect, you can pause here to give some explanation.
It could be useful to bring a glass prism to the classroom to give a practical demonstration of light diffraction.
For what concerns the Doppler effect, the example of the ambulance approaching and or recessing from us will be sufficient for what we need in the following.
On the other hand, if you want to stimulate your students to reflect on finer details about astronomical redshift, you can propose some extra readings like these ones:
http://www.esa.int/Science_Exploration/Space_Science/What_is_red_shift
http://astronomy.swin.edu.au/cosmos/c/cosmological+redshift

An expanding Universe:
Hubble reprises these observations and measures both the red-shift and the distance of galaxies. He finds that a galaxy's red-shift increases with the distance of the galaxy from the observer. In other words, the further the galaxy is, the faster it recedes from us. Edwin Hubble has just discovered that the Universe is expanding.

Such a discovery may lead to think that we are placed in a special point of the Universe – namely its centre – as everything around us is getting away from us. The fact is that any observer in any other point of the Universe would observe the same thing: every other object is recessing at a speed proportional to its distance.

Here you can gain some insight on this concept.

https://www.youtube.com/watch?v=i1UC6HpxY28

This is the Hubble law and it is plotted in Fig. 2 showing that the recessional velocity is proportional to the object's distance:

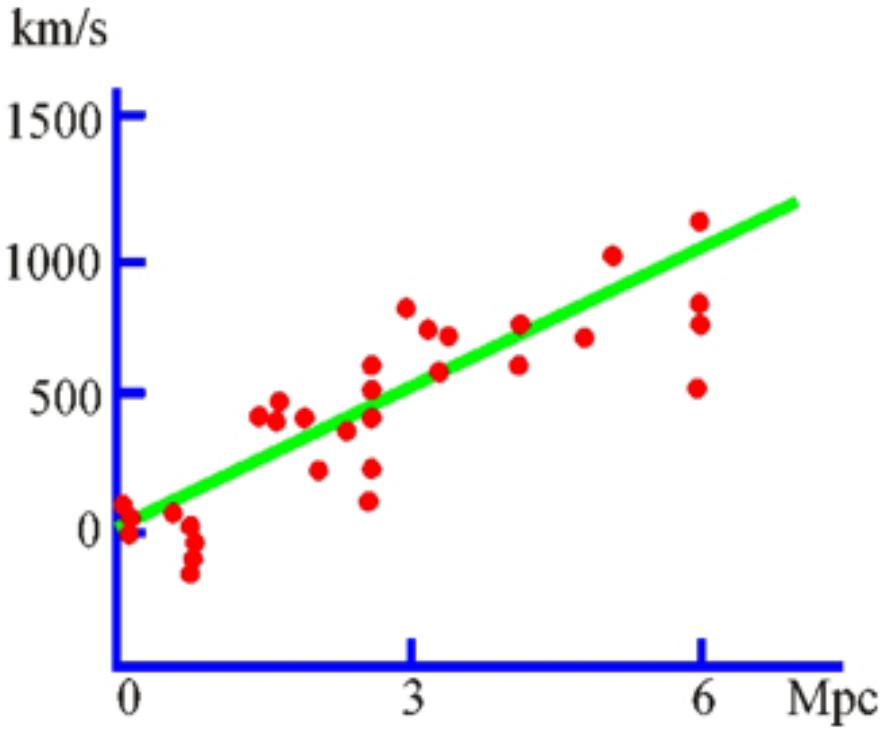


Figure 2: The Hubble law.

It is a ground-breaking discovery that proves that the Universe is not static as previously believed. On the contrary, it has a history, it was different in the past and it continues to evolve. It is now thought to be the result of a Big Bang that took place around 13.7 billion years ago, an age that we were able to infer thanks to measurements like the one by Hubble.

The expansion rate provides us with information on the age of the Universe and it can be estimated by the Hubble plot. As you can see from Fig. 2, the best fit to the observational data points is a straight line. The slope of the line, H_0, is called the Hubble constant. As we will see in this lesson, the age of the Universe can be estimated as $T = 1/H_0$. Hubble's discovery is hence crucial to retrace the history of the Universe.

For those who are curious:

A second method to determine the Hubble constant is provided by the Cosmic Microwave Background (CMB), the oldest observed astronomical messenger. The value of H_0 determined with the CMB differs slightly from the one obtained with the Hubble diagram. Such a discrepancy could point to some underlying new physics in the Universe yet to be discovered.

TEACHERS GUIDELINES

The Cosmic Microwave Background represents a huge chapter of modern cosmology. We do not recommend to go into the details here. The main point for your students to take away is that there is often more than one way to tackle a question and solve a problem. Different methods may give slightly different results. If this is the case, either we can perfectly account for the discrepancy in terms of experimental errors, or we might actually be faced with valuable insight on the problem at hand.
As a second point of interested, the experimental discovery of the CMB is a rather fun (and rare) episode of serendipitous discovery. Still worth a Nobel Prize.

Define goals and/or questions from current knowledge

Even if the fist measurements by Hubble were made about ninety years ago, at present we have measured only a small fraction of the velocities and distances of visible galaxies. So, we only have a few data points to verify if the expansion rate of the Universe is the same everywhere and in every direction. The Hubble relation continues to provide us with a helpful tool to map the Universe in space and time thanks to the fact that distances can be inferred by a simple red-shift measurement. In this exercise, we will repeat Hubble's observations by using modern astronomical methods. In fact, we will use a fundamental method in modern cosmological research.

Take a few minutes to discuss the following questions:
- Why did it take such a long time to understand that the Universe was not limited at our own Galaxy?
- What is the impact of the discovery of the expansion of the Universe?
- Does it make sense to talk about the "beginning" of the Universe?
- What are the possible scenarios for the Universe expansion?

Hypotesis generation & design

Generation of Hypotheses or preliminary explanations

We now want to retrace Hubble's process and reproduce his analysis in order to achieve our final goals:

1. Estimate H_0.
2. Calculate the age T of the Universe.

Before we dive in, let's check some basic concepts:

Formative assessment questions:

1. What is an absorption line?
   1.1. The light emitted by an astrophysical object.
   Feedback: Usually, objects emit a spectrum composed of many wavelengths and not just one (a line). Moreover, an absorption line indicated a wavelength that is missing (i.e. absorbed) rather than emitted.

   1.2. A dark line in a very specific and narrow wavelength range (or colour) in the light spectrum.
   Correct, congratulations!

   1.3. The light observed by optical telescopes.
   Optical telescopes usually observe a wide range of wavelengths that correspond to optical light (i.e. visible by the naked eye). To observe a spectrum, and therefore absorption lines, you need a spectrometer.

2. Is our Universe static or dynamic and how did Hubble find out?
   2.1. Our Universe is expanding. Hubble inferred it from the observation of the recessing velocities of distant galaxies.
   Correct, congratulations!

   2.2. Our Universe is expanding. Hubble inferred it from measurements of the Cosmic Microwave Background.
   Yes, our Universe is expanding. However, the CMB was not discovered until 1964, more than 10 years after Hubble's death.
   2.3. Our Universe is static. Hubble inferred it from the light spectra of galaxies.
   Our Universe was believed to be static for a very long time, but Hubble showed that this is not the case (thanks, indeed, to light spectra of galaxies).

According to what you have learnt so far, what do we need to achieve our goals, in terms of:

1. Experimental tools?
2. Sources to observe?
3. Mathematical relations to analyse the data?

Design/Model

1. We will simulate data taking at an optical telescope working with a TV camera and a spectrometer.
2. By operating these instruments, you will observe several galaxies located in selected areas of the sky and will be able to measure their luminosity and the wavelength of some absorption lines.
3. From the data collected, you will be able to calculate the galaxy's velocity in km/s thanks to the Doppler shift's effect and its distance in Mpc by comparing its apparent and absolute luminosity. You will then plot a graph of the velocity (y-axis) as a function of the distance (x-axis).

The galaxy clusters that will be observed have previously been selected in order to facilitate the determination of the Hubble law and the value of the Hubble constant, H_0. As we will see, the inverse of H_0 will give you an estimate of the age of the Universe.

Focus:

A parsec (or pc) is a unit of length widely used in Astronomy. It is roughly equal to 31 trillion km (31×10^{12} km). Given that the closest star to the Solar system is located at about 1.3 pc from the Sun and that the radius of the Milky Way is about 20/30 kiloparsecs (kpc), you can easily see how this unit is much handier for astronomical distances than meters or even kilometers.
To give you a taste of distance scales in the Universe, the kpc is appropriate for galactic distances (i.e. within our own Milky Way), megaparsec (Mpc = 1 million pc) for mid-distance galaxies, and gigaparsec (Gpc = 1 billion pc) for the most distant galaxies.

To know more: https://en.wikipedia.org/wiki/Parsec

How to use the instrument.
The telescope that we will "operate" has two instruments mounted on it: a TV camera that allows to look at galaxies and guide the telescope to the right position; and a spectrometer. A spectrometer is an instrument able to decompose the light in its components. The spectrum will then be displayed: you will see a plot of the received light intensity as a function of its wavelength. When the number of collected photons is large enough, you will be able to distinguish the absorption lines of the galaxy, in particular the calcium's H and K lines, and to measure their wavelength λ_m. You will notice that the value of λ_m will be larger than the H and K wavelengths l measured in a laboratory for stationary targets: $\lambda_H = 396.8$ nm and $\lambda_K = 393.4$ nm. The shift between l and λ_m is called Doppler shift and is due to the galaxy's recessing velocity. The spectrometer will also measure the galaxy's apparent magnitude from the number of photons collected.

Planning & investigation

Plan investigation

Welcome to an astronomical observatory! We will simulate a night of observations collecting data and we will draw conclusion on the age of the Universe from them.

In this section, we will see together how to collect data to produce a galaxy spectrum and how to analyse them. In the next section, you will be given several spectra and you will work autonomously to carry out the analysis.

We will watch a series of videos created with a software developed to simulate the operation of a spectrometer mounted on a telescope located on the top of a mountain. It is built to appear realistic and to give you first-hand insight on how an astronomer collects and analyses research data. The software window shows the control panel and the screen as they appear in the observatory control room.

Video 1:

Notice that at the beginning the dome is closed and the telescope is off.

The first thing to start a night of observation is to open the dome. The dome will now open giving you the view from the finder scope. The finder scope is mounted on the side of the main telescope and points in the same direction. The field of view of the finder scope is much larger than the one of the main instrument and it's used to locate the objects that we want to measure. A CDD camera mounted on the finder scope allows to display the field of view on the monitor. Notice that astronomers do not need to look at object through an eyepiece.

On the control panel, locate the command that gives the status of the monitor (it will be on "finder"). Take a moment to note that the stars drift on the monitor. This effect is due to the Earth's rotation and it gets more evident at higher magnifications of the finder scope.

Hence, in order to keep an object centred in the spectrometer window, we need to activate the tracking control of the telescope. To do so, we click on the "tracking" button. The telescope will now turn in sync with the stars.

INSERT HERE VIDEO 1: https://youtu.be/hVR7UEEvz-I.

Before we can collect data, we need to:

a. Select a field of view (one is currently selected).
b. Select an object to study (one of each field of view).

In the next videos we will select five fields of view from a list available within the software. We will then select one galaxy per field (a total of five galaxies) and collect the data with the spectrometer.

An astronomer would have chosen these fields before going to the observatory by:

a. Selecting the objects visible during that night.
b. Researching the celestial coordinates (Right Ascension and Declination of the objects in a catalogue).

Video 2:

In this video we will select our first field of view from a list. The fields are listed through their celestial coordinates. The first number represents the Right Ascension, measured in hours/minutes/seconds and the second the Declination, measured in degrees. Once we select the field, notice that the telescope “slews” (moves quickly) to the selected RA and Dec. coordinates. The screen shows the sky image that was captured by the CCD camera of the telescope.
The screen has two magnifications:
“Finder” is the view through the finder scope that gives a wide field and has a red square that identifies the instrument field of view.
“Telescope” is the view through the main telescope with red lines identifying the position of the spectrometer slit.
As in any image of the night sky, stars and galaxies are visible on the screen. You can easily recognize bright galaxies in this simulation since their shape is clearly different from the point-like image of stars. However, distant and faint galaxies can look like stars as we are unable to see their shape.

When switching to telescope view, the slit will already be placed on the object to study. We can adjust the position by slewing the telescope with the commands N, S, E, W. The red light marks that the telescope is moving in that direction. As in any real observatory, it takes some practice to point an object with the telescope. We can adjust the slew rate by clicking on the relative button (1 being the slowest and 16 the fastest).
The higher the flux in the spectrometer, the stronger the signal that will be detected and the shorter the time needed to get a usable spectrum. That is why we want to place the slit on the brightest part of the galaxy. If you point to the faintest part, you will still get a spectrum but it will require a much longer exposure time. If you place the slit completely off the galaxy, you will then get a spectrum of the sky, basically just random noise.
In the video we will slew to a different object to better highlight how the telescope works.

INSERT VIDEO 2 HERE: https://youtu.be/DHxpr3uKV-0.

Video 3:

The galaxy is now rightly positioned in the spectrometer's slit, we are about to collect data on our object.

In order to take data, we need to access the Spectrometer. A new window pops up showing an empty diagram and a series of variables. Let's review them:

Graph:

Wavelength (angstroms): Wavelength of the collected photons, measured in Angstroms (10^{-10} m).

Intensity: Relative intensity of light from the galaxy at the position marked by the cursor in the measurement mode.

Lower portion of the window:

Object: the name of the object being studied

Apparent magnitude: the visual magnitude of the object

Photon count: The total number of photons collected so far.

Photons per channel: The number of photons averaged over the total number of channels in the spectrometer.

Integration (seconds): The number of seconds it took to collect data

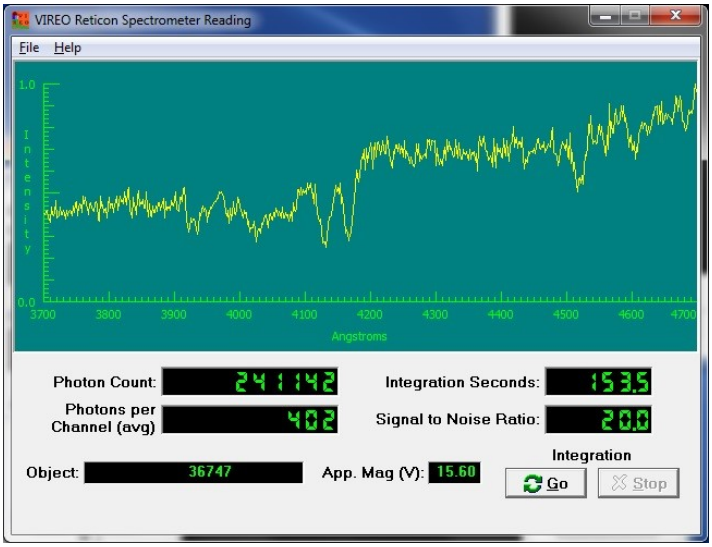
Signal-to-noise Ratio: A measurement of the quality of the data taken to distinguish the H and K lines of calcium from the noise. Try to get a signal-to-noise ratio of at least 10. For faint galaxies, this may take some time.

We start the data acquisition. As you can see, as the integration time progresses, the galaxy spectrum starts to appear in the graph. Our goal is to measure the wavelengths of the characteristic H and K calcium lines which appear in the spectrum. These lines are approximately 40 Å apart; the K line is first, followed by the H line.

Photons are collected one by one and we must collect a number large enough to allow us to clearly identify the lines' wavelengths. The more photons we collect, the higher the signal-to-noise ratio will be and the absorption lines will be easier to isolate.
To check the progress of our data taking, we stop the integration and check the signal-to-noise ratio and the total number of photons collected. Continuing the data taking, the spectrum will appear clearer.

INSERT VIDEO 3 HERE: https://youtu.be/wY-ADnD08E4.

Let us now pause to extract the necessary information from this image:



At the end of the next section you will find a spreadsheet that you can use to write down all the necessary data. We will do it together for the first object.

Galaxy name: 36747.

Photon number: 241142.

App Mag: 15.60.

This is all the information we can gather from this image.

To go further, we will now proceed to analyse the spectrum.

Before we proceed, take a moment to look at the spectrum. Which two spectral lines to you think are the H and K calcium absorption lines? Here is a tip: remember that the wavelengths measured in the laboratory are λ_H = 396.8 nm and λ_K = 393.4 nm and that we expect a red shift (a shift towards higher wavelengths).

Formative assessment question:

If the wavelengths of the H and K lines are λ_H = 396.8 nm and λ_K = 393.4 nm respectively, what value do they have in meters and in angstrom?

1. $\lambda_H = 3.968 \times 10^{-9}$ m = 39.68 Å;
   $\lambda_K = 3.934 \times 10^{-9}$ m = 39.34 Å.

   False.
   A nm is equal to 10^{-9} m, therefore 396.8 nm = 396.8×10^{-9} m.

2. $\lambda_H = 3.968 \times 10^{-7}$ m = 39.68 Å;
   $\lambda_K = 3.934 \times 10^{-7}$ m = 39.34 Å.

   False.
   The measurement in meters is correct, however 1 Å = 10^{-10} m. In this answer 1 Å is set equal to 10^{-8} m.

3. $\lambda_H = 3.968 \times 10^{-7}$ m = 3968 Å;
   $\lambda_K = 3.934 \times 10^{-7}$ m = 3934 Å.

   Correct, congratulations!

Video 4:

The galaxy spectrum collected in video 3 has been saved and stored.

In this video we will use a tool to manipulate it in order to measure the wavelengths of the H and K line.

We upload the saved spectrum into the Spectrum Measuring Engine. As a reference point, we can superimpose a template of the nominal position of calcium lines and appreciate the shift towards higher wavelengths due to the galaxy motion.

To get a more precise measurement, we will zoom in a smaller wavelength range around the two lines and then use the cursor to get the wavelength of the line peak.

INSERT VIDEO 4 HERE: https://youtu.be/OXGv7bHeYxA

Go back to your spreadsheet and write down the two measured wavelengths as they appear in the figures below:

Notice that we can ignore the decimals. On the x-axis we do not have enough sensibility to appreciate correctly even the units, but we can make a sensible guess on those.

Now that we have completed the data taking on the first source, you will be able to conclude the exercise on the next four sources on your own.

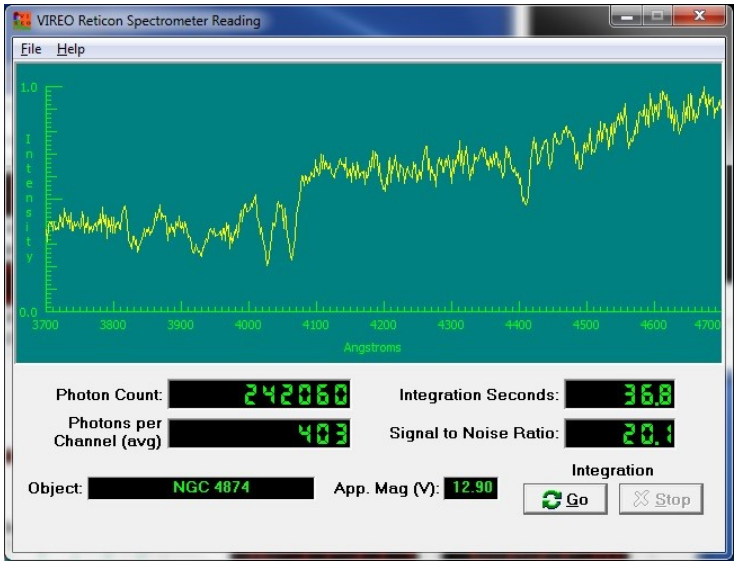
Perform investigation

In this section, you will be provided with the spectra of four galaxies selected in four different fields of view.

For each spectrum, you will have to extract from the images the relevant quantities and write them down on your spreadsheet. Let's begin!

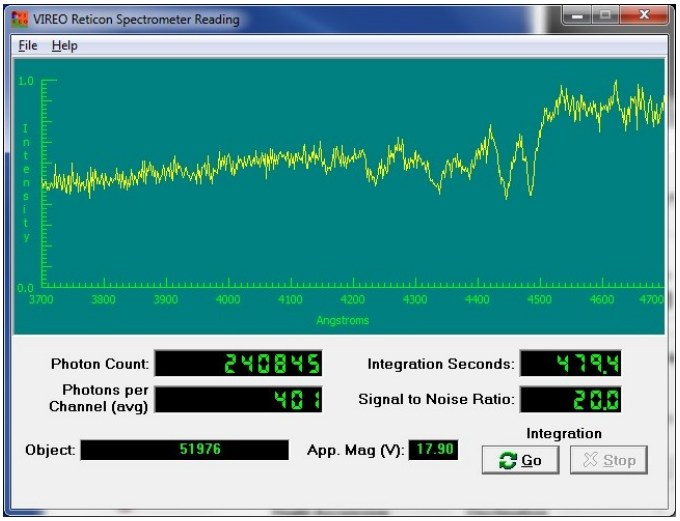
Field: RA = 12h 59m 35s, Dec = 27 deg 57' 36".

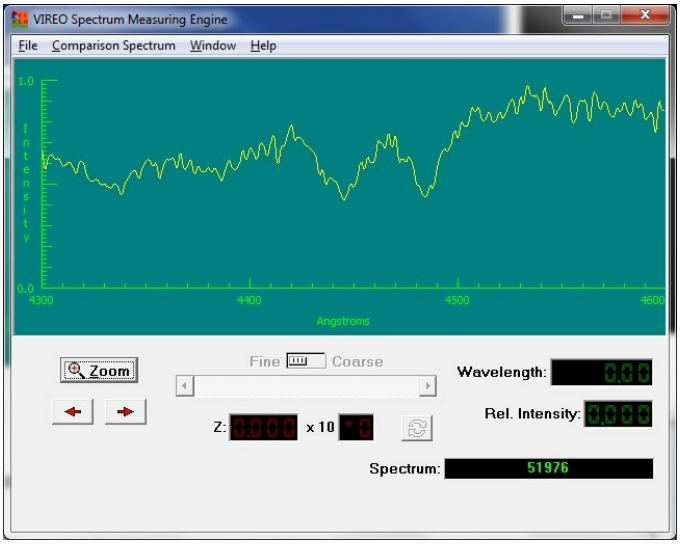
Source 2:



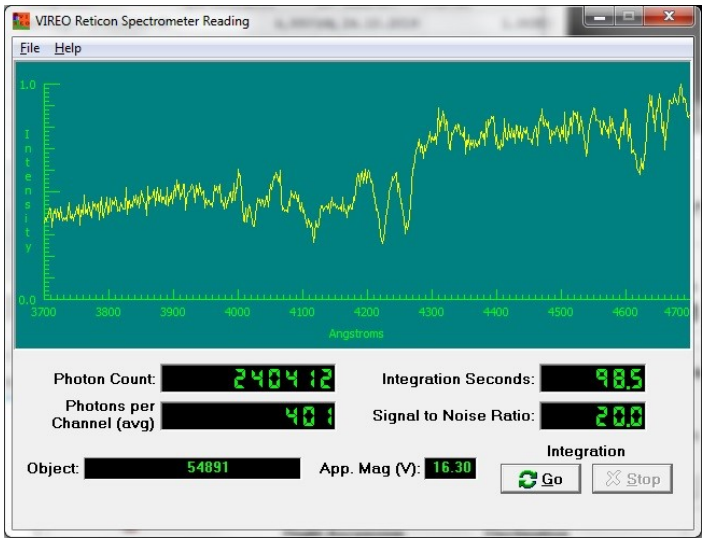
Field: RA = 14h 32m 44s, Dec = 31 deg 33’ 48”.

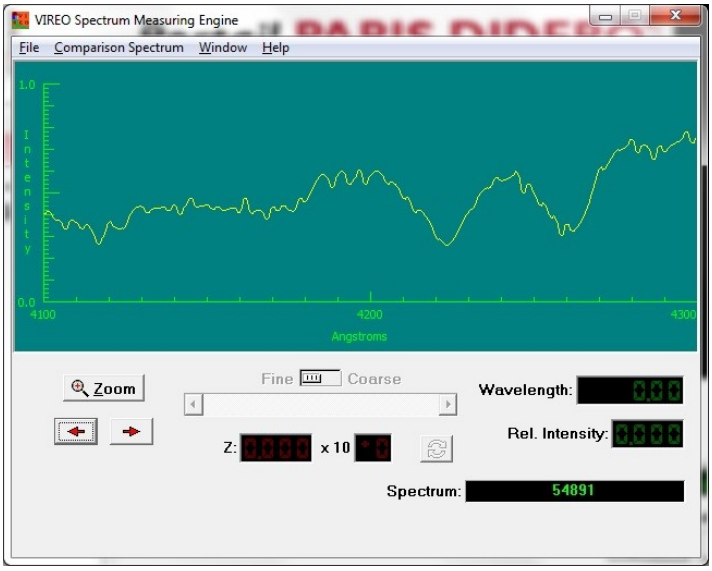
Source 3:



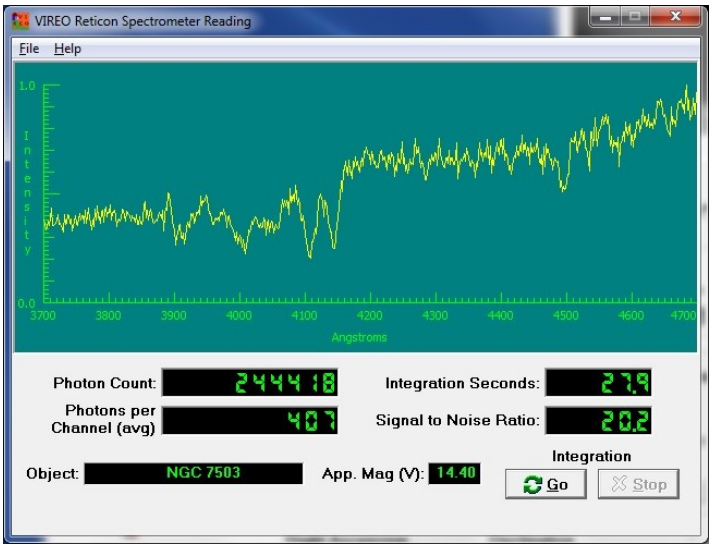


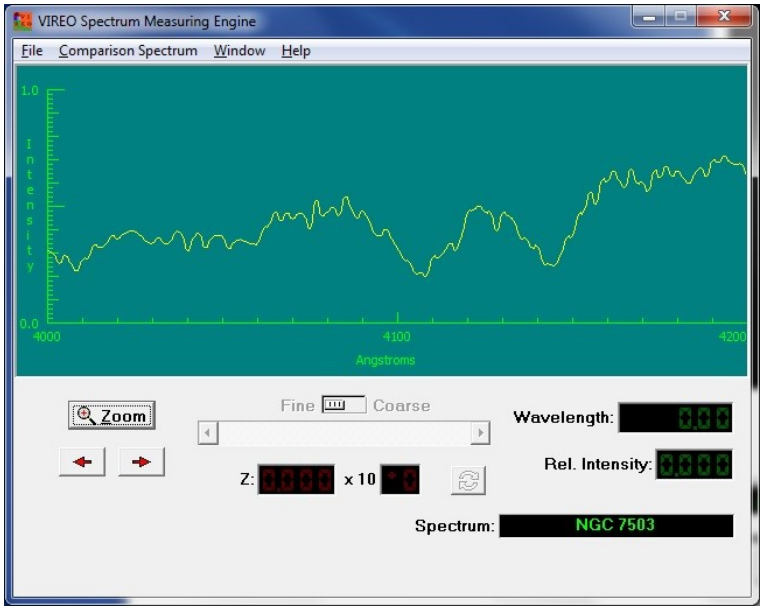
Field: RA = 15h 22m 42s, Dec = 27 deg 40’ 22”.
Source 4:





Field: RA = 23h 10m 42s, Dec = 07 deg 34’ 01”.
Source 5:





Note: once you have filled in the data of your spreadsheet here below, remember to download it on your computer or you will not be able to access it in the next section of the exercise.

INSERT DATA SPREADSHEET HERE

Analysis and Interpretation

Analysis and Interpretation: Gather result from data

Now that we have collected the data, we can use them to determine the distance and velocity of each galaxy. We will use the following formulae:

$$M = m + 5 - 5 \log D$$

or

$$\log \mathrm{D} = \frac{m-M+5}{5} \qquad \text{Eq. 1}$$

where *D* is the distance of the galaxy, *M* and *m* its absolute and apparent magnitude, respectively. We measure *m* and assume a value for *M* in order to calculate *D*.

For what concerns the velocity *V*, we have two measurements:

$$V_H = c\frac{\Delta\lambda_H}{\lambda_H} \qquad \text{and} \qquad V_K = c\frac{\Delta\lambda_K}{\lambda_K} \qquad \text{Eq. 2}$$

Where $c = 3 \times 10^5$ km/s is the speed of light and:

$$\Delta\lambda_H = \lambda_{Hmeasured} - \lambda_{Hlab} \quad \text{and} \quad \Delta\lambda_K = \lambda_{Kmeasured} - \lambda_{Klab} \quad \text{Eq. 3}$$

Recalling that λ_{Hlab} = 3968 Å and λ_{Klab} = 3934 Å, use the data on your spreadsheet to calculate all the $\Delta\lambda$ as in Eq. 3.

Finally, use Eq. 2 to calculate the two values of the galaxy velocity and then average them to obtain the mean velocity.

1. **The Hubble constant:**

We are very close to find our final result!

Formative assessment question

Do you remember what is the final goal of our exercise? What are the two fundamental quantities that we want to obtain?

1. Galaxy distances and velocities.
   No, sorry, these are the quantities that we will use to achieve our final goals.

2. Galaxy age and the Hubble constant.

   You are partially correct: we want to obtain the Hubble constant, but we will not calculate the age of the galaxies.

3. The Hubble constant and the age of the Universe.

   Correct, congratulations!

You can now finally plot the Hubble diagram!

In order to do so, you need the data spreadsheet you filled in the previous section and the spreadsheet here below.
Report in the appropriate column the distance D in Mpc and mean velocity V in km/s that you calculated for each galaxy and the plot will appear automatically.

INSERT SPREADSHEET “Hubble diagram” HERE.

Now, if you have the possibility to print the diagram, do it. Otherwise, you will have to reproduce it on a sheet of paper.

Draw the straight line that starts from the origin and best fits your data points. The slope of the line is the Hubble constant H0. To calculate it, chose a point on the line you drew (be careful not to take one of your data points but a point on your best-fit line) and measure its D and V values. Then:

$$H_0 = \frac{V}{D} \quad \text{Eq. 4}$$

H0 will be in the units of km/s/Mpc.

On your data spreadsheet you can now report the value of the Hubble constant you obtained. Mark down the values of D and V you used.

2. The age of the Universe:

The Hubble law in Eq. 4 can be used to determine the age of the Universe. Let's see how.
As you know, when you travel at a constant velocity v (for instance by car), you can calculate the time of your trip by the formula:

$$t = d/v$$

Where d is the distance you want to cover. For example, if you need to travel for 100 km and you go at a speed of 50 km/h, it will take you 2 h to arrive.

By comparing Eq. 4 and 5, you can easily see that:

$$T = 1/H0 \quad \text{Eq 5.}$$

The reciprocal of the Hubble constant has the units of a time and, in fact, gives us an estimate of the age of the Universe.

We are now faced with one last issue: units. As you now know, H0 is measured in km/Mpc/s. We would like the age of the Universe in years. Therefore, we need the two conversion factors:

$$1 \text{ Mpc} = 3.1 \times 1019 \text{ km} ; \quad 1 \text{ y} = 3.1 \times 107 \text{ s.}$$

Once you calculated the age of the Universe, mark it on your data spreadsheet.

Conclusion & evaluation

Conclude and communicate result/explanation

1/ Write a 15 lines report on what you have done addressing the following points (context, methodology, results, discussions).

2/ Record a 1 minute video or audio on what you have done addressing the following points (context, methodology, results, discussions). If you use a video, you can show your results (in the form of plots and schemes).

Evaluation/reflection

1. Compare your results on H_0 and T with your classmates. Try to point out the possible sources of discrepancy within the class. What are the critical points of the exercise? What could the main sources of error be?
2. Now go online and find the present values of H_0 and T present in the literature (for a methodology close to the you used in the exercise). How do these values compare with the ones you found?
3. What did you find the most interesting and the last interesting part of this exercise? Could be the general information on the life of the Universe, the methodology, the daily life of an astronomer and so on…
4. Do you feel that you have gained relevant information on the physics of the Universe?
5. Do you feel that you have gained relevant insight on the daily work of astronomers?
6. Do you feel that you have learned new tools (mathematical/practical/conceptual?

Always try to justify your answers in at least one or two lines.

Consider other explanations

In the literature you might have found different values for H_0 as well as different methods to measure it.

Try to summarize these differences and their meaning in terms of our interpretation and understanding of the expansion of the Universe.

TEACHER GUIDELINES

If you found the exercise successful, you may try to engage your students with related concepts that were not directly explained. Here are two topics of further discussion:

1. How the Universe is expanding and why. Here is a video that you can show to the class to sparkle discussion: https://www.khanacademy.org/partner-content/amnh/the-universe/universe/v/our-expanding-universe
2. If the Universe is expanding and distant galaxies are dragged away, how come that:
    a. The Sun, the planets and us do not stretch and get away from each other in the same way?
    b. Nearby galaxies (like Andromeda) are actually blue-shifted, i.e. are getting closer to us?