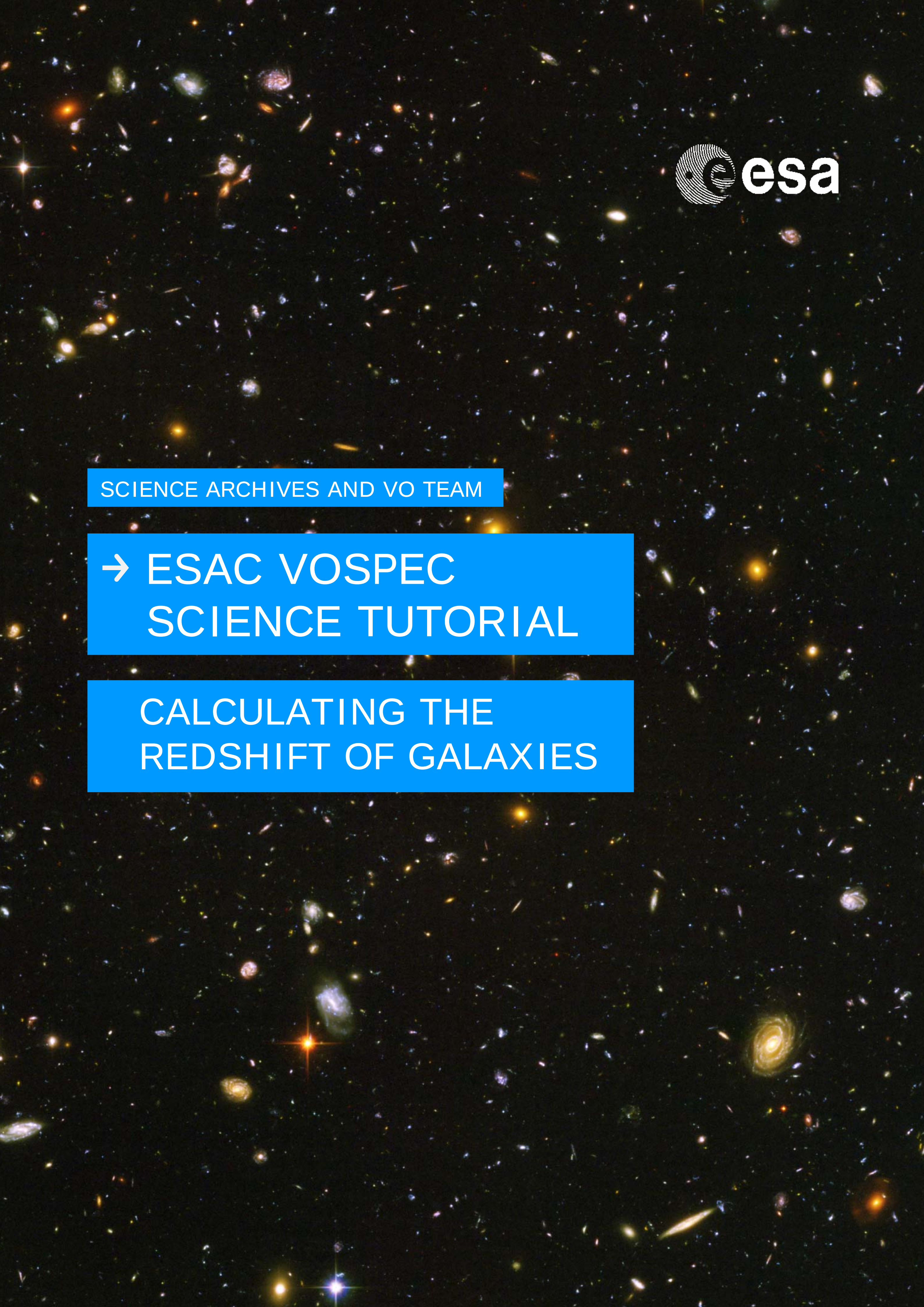

SCIENCE ARCHIVES AND VO TEAM

→ ESAC VOSPEC SCIENCE TUTORIAL

CALCULATING THE REDSHIFT OF GALAXIES

Tutorial created by Phil Furneaux, Lancaster University,
and Deborah Baines, Science Archives Team scientist.

This tutorial can be found online at:
http://www.sciops.esa.int/SD/ESAVO/docs/VOSpec_Redshift_Tutorial.pdf

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http://archives.esac.esa.int

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ESAC Science Archives and Virtual Observatory Team

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BACKGROUND

European Space Agency
Agence spatiale européenne

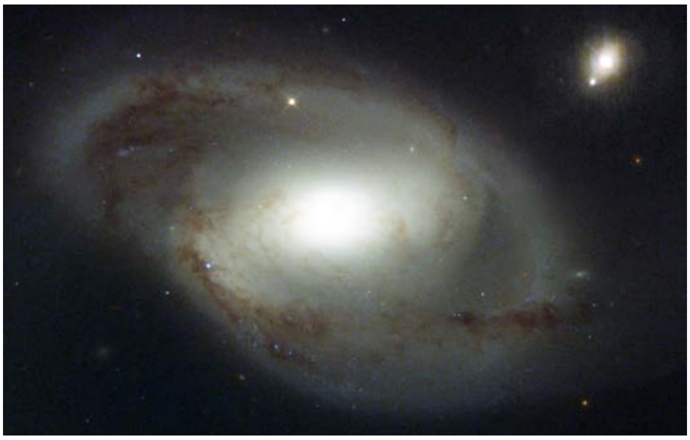
1 BACKGROUND

1.2 THE TRIANGULUM GALAXY (M33)

The Triangulum Galaxy (M33)

The Triangulum Galaxy (M33) is a spiral galaxy and the third largest galaxy within the Local Group of galaxies, which includes the Milky Way Galaxy, the Andromeda Galaxy (M31) and about 30 other smaller galaxies. M33 is approximately 2.5 million light years (or ~820,000 parsecs) from Earth, and located in the constellation Triangulum. It is one of the most distant permanent objects that can be viewed with the naked eye. This galaxy is small compared to its large neighbours the Milky Way and M31, but is still of average size for spiral galaxies in the universe, containing approximately 40 billion stars. The Local Group of galaxies are gravitationally bound to one another, with the centre of mass lying between the two largest members, the Milky Way galaxy and M31. Therefore, we see many of the Local Group galaxies moving towards us. M33 is one of the galaxies moving towards us, and has a redshift of -0.000607 (with the minus sign indicating a blueshift). Since redshift, z, can be expressed as $z \approx v/c$ (when v is much less than the speed of light), and v= velocity and c = speed of light, M33 is travelling towards us at a speed of ~180 km/s.

1.3 QUASARS AND QSOs



The QSO, Mrk 205 (right), and spiral galaxy, NGC4319 (left)

Quasars stand for 'quasi-stellar radio sources' and are believed to be a compact region in the centre of a massive galaxy surrounding its central supermassive black hole. The first quasars were discovered with radio telescopes in the late 1950s, however only ~10% have strong radio emissions ('radio-loud'). Hence the name 'QSO' (quasi stellar object) is used, in addition to quasar, to refer to these objects. More than 200,000 quasars are known, and all show very high redshifts, between ~0.06 and ~7.09. They are among the most luminous, powerful, and energetic objects known in the universe.

1.4 SPECTROSCOPY

(Below is adapted from the Caltech, IPAC outreach web pages: http://www.ipac.caltech.edu/Outreach/Edu/Spectra/spec.html).

Spectroscopy is a very important tool in astronomy. It is the detailed study of light from an object. Light is energy that moves through space and can be thought of as either waves or particles. The distances between the peaks of the waves of light are called the light's wavelength. Light is made up of many different wavelengths. For example, visible light has wavelengths of about 1/10th of a micrometre.

Spectrometers are instruments which spread light out into its wavelengths, creating a spectrum. Within this spectrum, astronomers can study emission and absorption lines which are the fingerprints of atoms and molecules. An emission line occurs when an electron drops down to a lower orbit around the nucleus of an atom and looses energy. An absorption line occurs when electrons move to a higher orbit by absorbing energy. Each atom has a unique spacing of orbits and can emit or absorb only certain energies or wavelengths. This is why the location and spacing of spectral lines is unique for each atom.

Astronomers can learn a great deal about an object in space by studying its spectrum, such as its composition (what it’s made of), temperature, density, and its motion (both its rotation as well as how fast it is moving towards or away from us).

There are three types of spectra which an object can emit: continuous, emission and absorption spectra. The examples of these types of spectra shown below are for visible light as it is spread out from purple to red, but the concept is the same for any region of the electromagnetic spectrum (from gamma-rays through X-rays, ultraviolet, visible, infrared, millimetre, all the way to radio).

1.4.1 CONTINUOUS SPECTRA

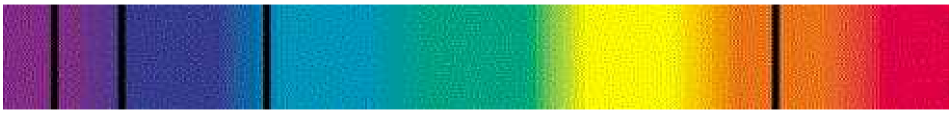
Continuous spectra (also called a thermal or blackbody spectrum) are emitted by any object that radiates heat (has a temperature). The light is spread out into a continuous band with every wavelength having some amount of radiation. For example, when sunlight is passed through a prism, its light is spread out into its colours.

A continuous visible light spectrum

1.4.2 ABSORPTION SPECTRA

If you look more closely at the Sun's spectrum, you will notice the presence of dark lines. These lines are caused by the Sun's atmosphere absorbing light at certain wavelengths, causing the intensity of the light at this wavelength to drop and appear dark. The atoms and molecules in a gas will absorb only certain wavelengths of light. The pattern of these lines is unique to each element and tells us what elements make up the atmosphere of the Sun. We usually see absorption spectra from regions in space where a cooler gas lies between us and a hotter source. We usually see absorption spectra from stars, planets with atmospheres, and galaxies.

Detailed image of our Sun's visible light spectrum



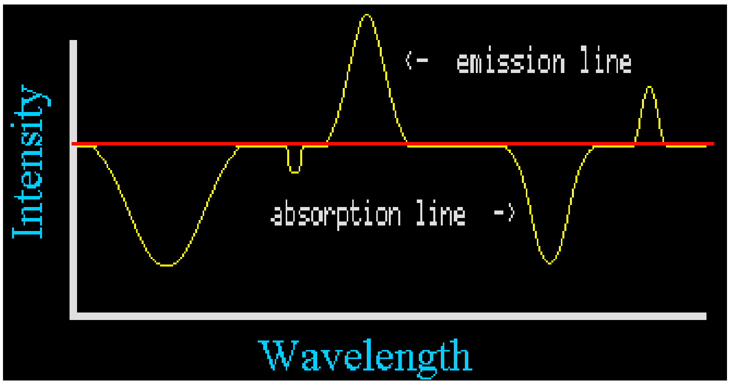
The absorption spectrum of hydrogen

1.4.3 EMISSION SPECTRA

Emission spectra occur when the atoms and molecules in a hot gas emit extra light at certain wavelengths, causing bright lines to appear in a spectrum. As with absorption spectra, the pattern of these lines is unique for each element. We can see emission spectra from comets, nebula and certain types of stars.

The emission spectrum of hydrogen

In practice, astronomers rarely look at spectra the way they are displayed in the above images. Instead they study plots of intensity, signal or flux versus wavelength. These plots show how much light is present or absent at each wavelength. A peak in the plot shows the position of an emission line and dip shows where an absorption line is. The spacing and location of these lines are unique to each atom and molecule.



The shape of the continuous spectrum (often referred to as the continuum) on a plot is dependent on temperature and motion of the emitting gas. In this simple plot it is shown as a flat line (red line), in reality it is usually a curved line. Also, many of the real data plots you will see have the wavelength or frequency on a logarithmic scale.

For more background information, see:

http://outreach.atnf.csiro.au/education/senior/astrophysics/spectroscopyhow.html

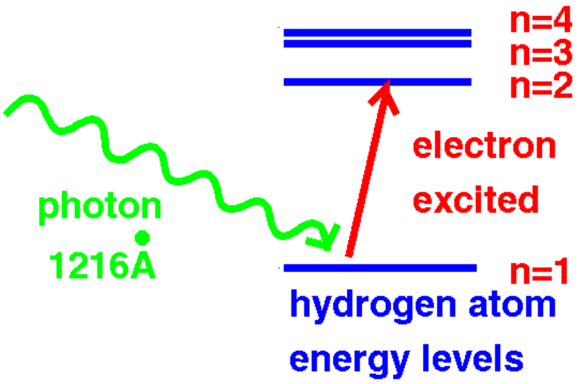
http://www.astronomynotes.com/light/s4.htm

http://loke.as.arizona.edu/~ckulesa/camp/spectroscopy_intro.html

http://csep10.phys.utk.edu/astr162/lect/light/absorption.html

1.5 THE HYDROGEN LYMAN ALPHA LINE

(Below is adapted from Dr J. Cohn's lecture notes at the University of Berkeley: http://astro.berkeley.edu/~jcohn/lya.html).



The Lyman series is the series of energies required to excite an electron in hydrogen from its lowest energy state to a higher energy state. The case of particular interest for cosmology is where a a hydrogen atom with its electron in the lowest energy configuration gets hit by a photon (light wave) and is boosted to the next lowest energy level. The energy levels are given by $E_n = -13.6 \text{ eV}/n^2$ and the energy difference between the lowest (n=1) and second lowest (n=2) levels corresponds to a photon with wavelength 1216 Angstroms. The reverse process can and does occur as well, where an electron goes from the higher n=2 energy state to the ground state, releasing a photon of the same energy.

The absorption or emission of photons with the correct wavelength can tell us something about the presence of hydrogen and free electrons in space. That is, if you shine a light with wavelength 1216 at a bunch of neutral hydrogen atoms in their ground state, the atoms will absorb the light, using it to boost the electron to a higher energy state. If there are a lot of neutral hydrogen atoms in their ground state, they will absorb more and more of the light. So if you look at the light you receive, intensity as a function of wavelength, you will see a dip in the intensity at 1216 angstroms, depending on the amount of neutral hydrogen present in its ground state. The amount of light absorbed ('optical depth') is proportional to the probability that the hydrogen will absorb the photon (cross section) times the number of hydrogen atoms along its path.

Because the universe has many high energy photons and hydrogen atoms, both the absorption and emission of photons occurs frequently. In Lyman alpha systems, the hydrogen is found in regions in space, and the source for the photons are quasars (also called qsos), very high energy light sources, shining at us from behind these regions.

THE TUTORIAL

European Space Agency
Agence spatiale européenne

2 CALCULATING THE REDSHIFT OF GALAXIES

GOAL: The overall goal of this tutorial is to compare the spectra of different galaxies, calculate their redshifts and hence search for evidence of the expansion of the Universe.

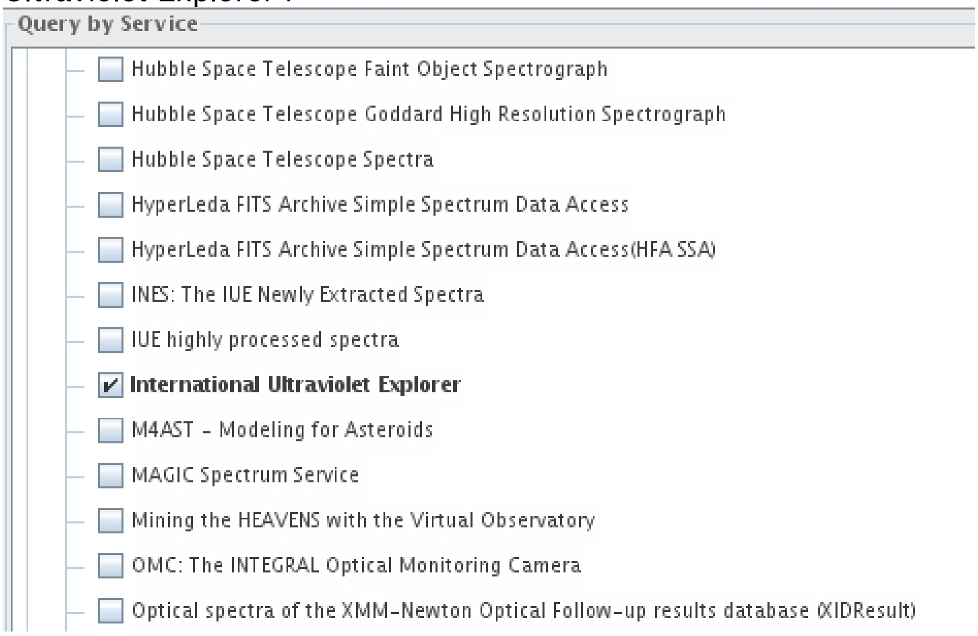
Note:

- This tutorial can be found online here: http://www.sciops.esa.int/SD/ESAVO/docs/VOSpec_Redshift_Tutorial.pdf

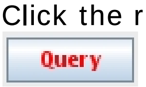
USES: The Virtual Observatory Tool VOSpec (a multi-wavelength spectral analysis tool).

1. Open VOSpec: http://esavo.esac.esa.int/webstart/VOSpec.jnlp
2. In the Target field type '**M33**', change the Size value to 0.1 (this is in degrees) and click the 'Query' button.

3. The Server Selector window opens. Select the Observational Spectra Services, in the left-hand side of the window in the 'Query by Service' region, by opening up the Observational Spectra Services tree. Select the service called 'International Ultraviolet Explorer':

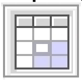


4. Click the red 'Query' button.

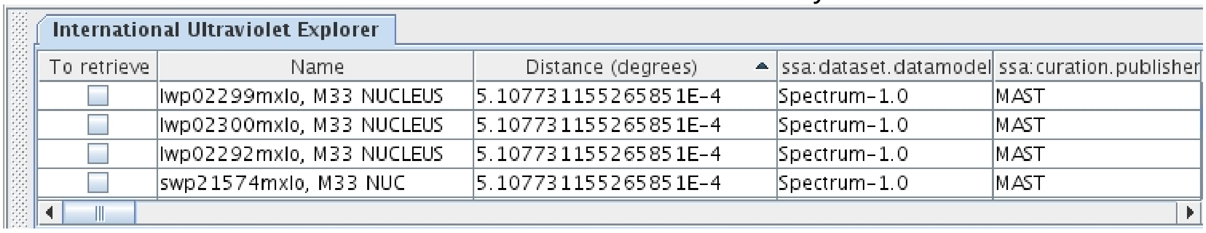


5. The spectra are then loaded into the 'Spectra List' region in the lower part of the main VOSpec window. Open up the tree structure to display the available spectra:

6. This list can also be viewed as a table by clicking the 'Tree/Table view' icon on the top right of the main VOSpec window:



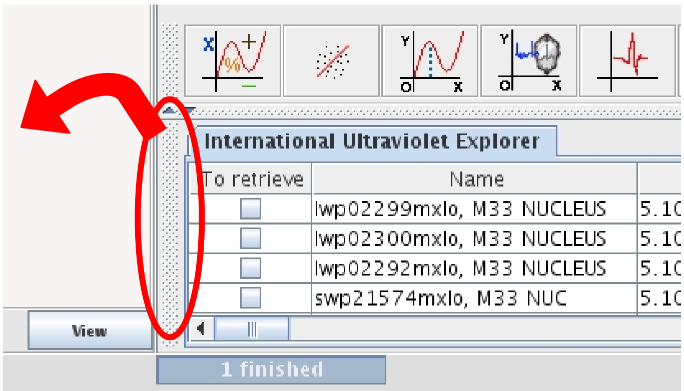
7. Change the view to table. Expand the 'Name' column to show the full name. Click on the Name column and other columns and see how they can be sorted:



International Ultraviolet Explorer

To retrieve	Name	Distance (degrees)	ssa:dataset.datamodel	ssa:curation.publisher
☐	lwp02299mxlo, M33 NUCLEUS	5.107731155265851E-4	Spectrum-1.0	MAST
☐	lwp02300mxlo, M33 NUCLEUS	5.107731155265851E-4	Spectrum-1.0	MAST
☐	lwp02292mxlo, M33 NUCLEUS	5.107731155265851E-4	Spectrum-1.0	MAST
☐	swp21574mxlo, M33 NUC	5.107731155265851E-4	Spectrum-1.0	MAST

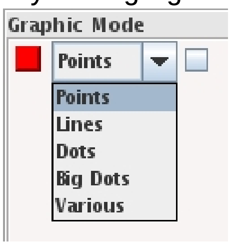
8. This view can be detached into its own separate window by clicking the left region and dragging it out:



To reattach the view, simply close the window.

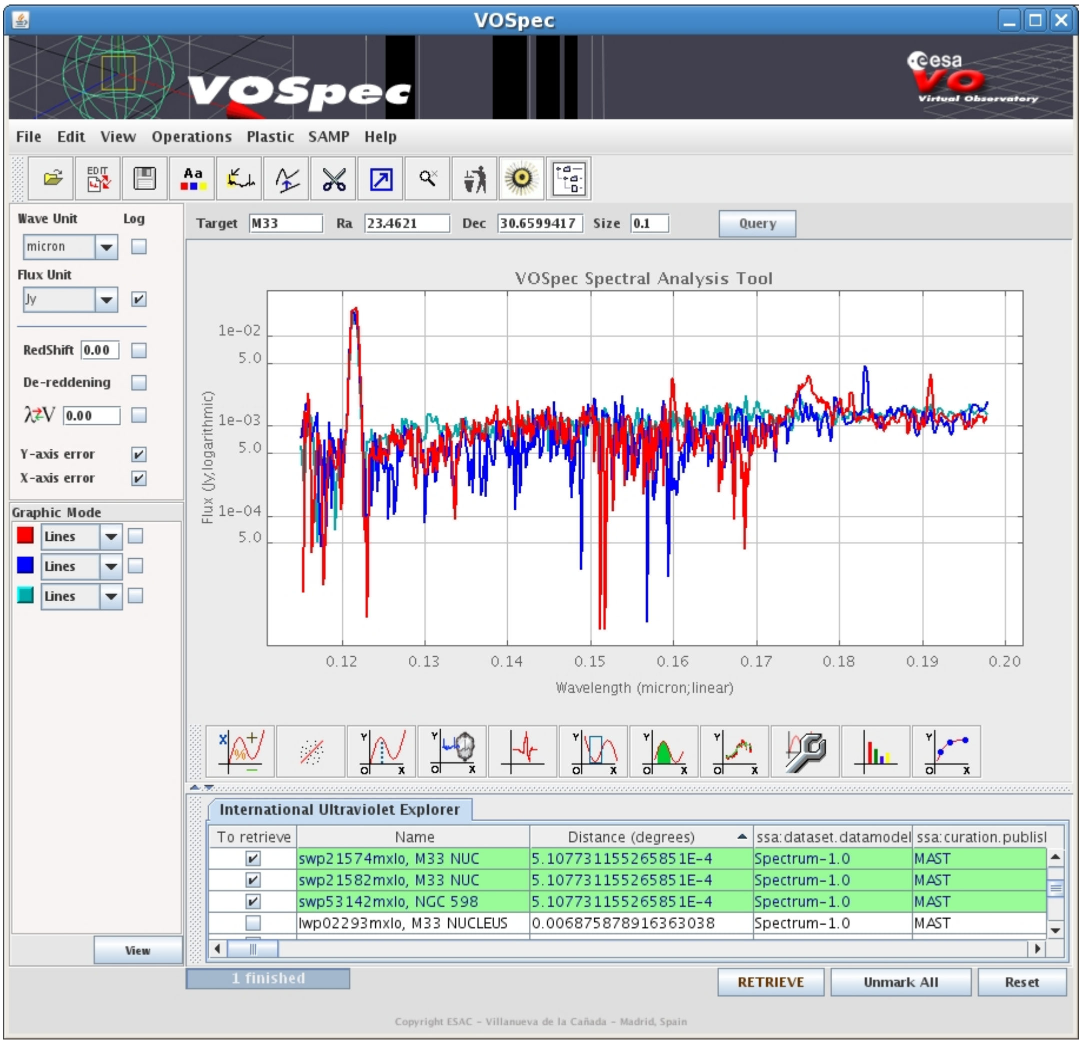
9. Select some of the spectra beginning with the name 'swp' (these are spectra from the Short Wavelength spectrograph of the International Ultraviolet Explorer, in the wavelength range 0.115 to 0.195 microns). Then click the 'RETRIEVE' button:

10. The spectra are now displayed in the main VOSpec window.
11. Try changing how the spectra are drawn, e.g. from points to lines, to dots:



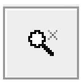
12. Change the spectra to be viewed as lines. To view all the spectra together, click the ‘View’ button at the bottom left.
13. On the left hand side, towards the top, untick the 'Log' box next to the Wave Unit:

14. Once unticked the spectra will redisplay with the x-axis (the wavelength axis) in linear, instead of logarithmic scale:

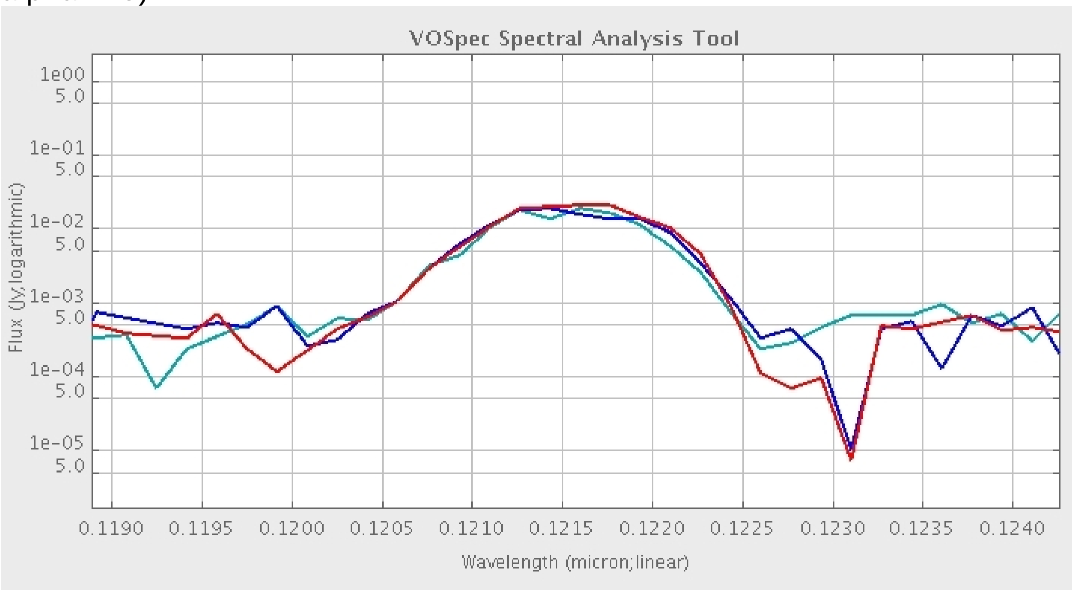


Note, the wavelength is shown in microns (micrometres), which are one millionth the size of a metre, or one thousandth the size of a millimetre.

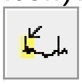
15. Try zooming in and out of the spectrum. Zoom in by clicking the left mouse button and dragging from top left to bottom right. Zoom out in a similar way by clicking the left mouse button and dragging from bottom right to top left, or by clicking the 'Unzoom' icon, located in the top menu and from View -> Unzoom:



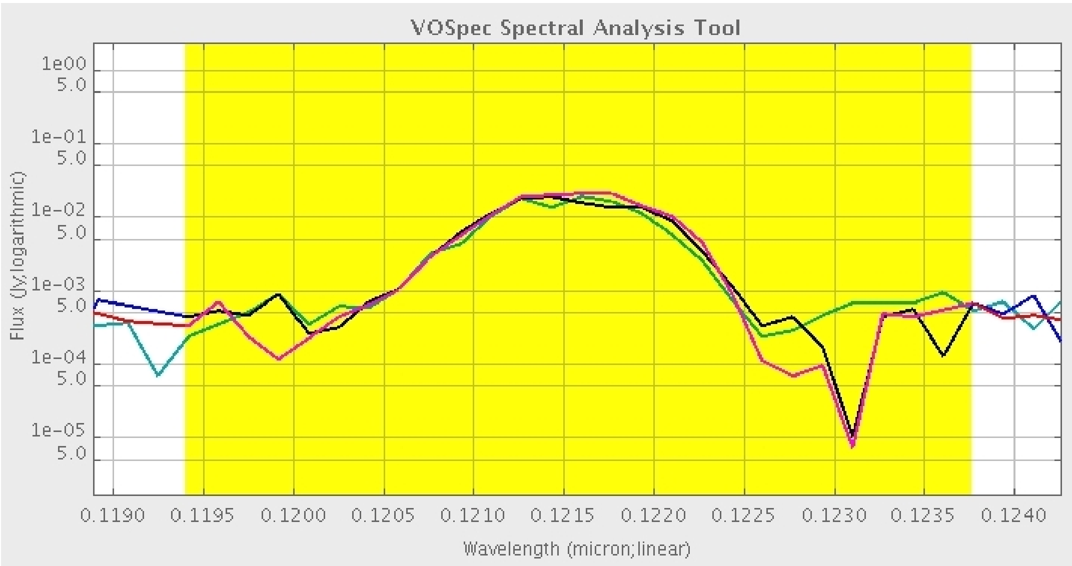
16. Zoom in on the strong emission line at ~0.1215 microns (the Hydrogen Lyman alpha line):



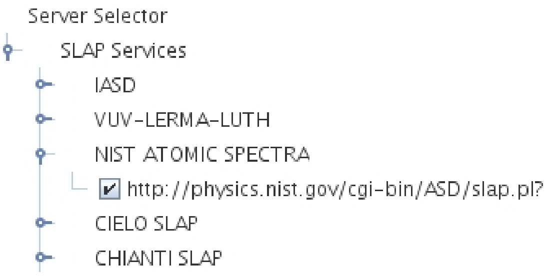
17. We can double check the identity of this line by searching through line identification databases. Select from the main menu Operations -> SLAP (or click on the SLAP icon):



18. Drag your mouse across the spectra so that the region turns yellow, from one side of the emission line to the other:

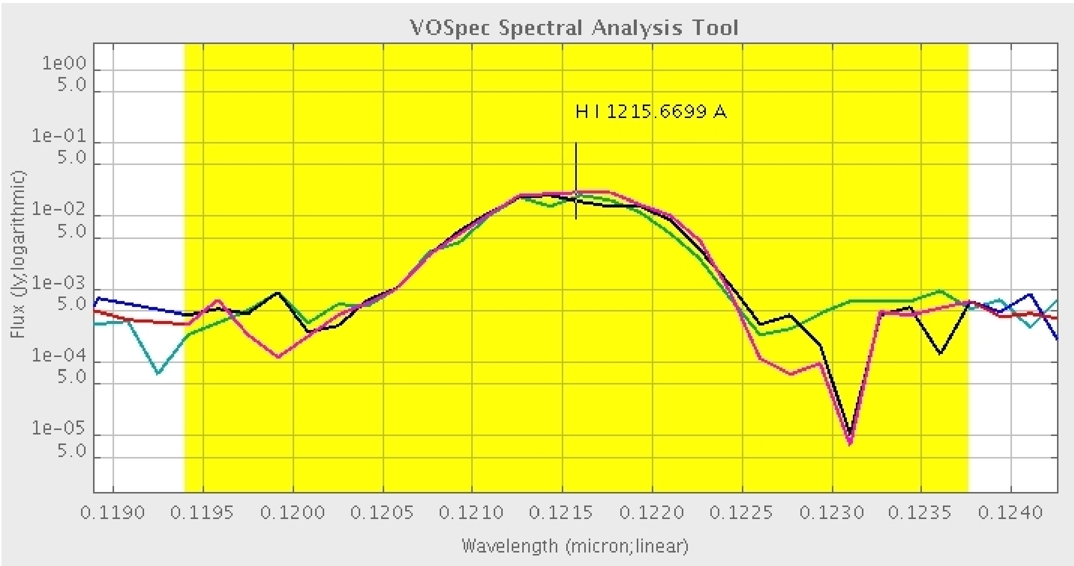


19. The Slap Viewer window will open. Open up the SLAP Services tree and select the NIST ATOMIC SPECTRA SLAP service:



20. Click the 'Select' button:

21. A table then loads in the lower region of the window, in the Slap Services Output panel. Go back to the main VOSpec window and move your mouse across the spectra. The line identifications, from the loaded database, are shown on the spectra:



22. The Hydrogen Lyman alpha line appears at 1215.67 Angstroms (one Angstrom, or Å = 10000 microns). *Be careful*, the NIST ATOMIC SPECTRA SLAP service is a very large database of radiative transitions in atoms and atomic ions for the first 99 elements in the periodic table, and for energy levels of the first 56 elements. The database is from the National Institute of Standards and Technology (NIST) in the US. There are many lines in this database that we would never expect to see coming from a star, galaxy, or any other astronomical body. Four Hydrogen (HI) transitions occur around 1215.67 Angstroms, but the Lyman alpha transition at 1215.6701 Angstroms is by far the strongest.
23. We are now going to search for the Lyman alpha emission line from a number of quasar galaxies and calculate their redshifts.
24. Go back to the main VOSpec window, unselect the SLAP icon, and click on the 'Reset' button.
25. In the Target field type '**3C 273**', keep the Size value as 0.1 and click the 'Query' button.

26. When the Server Selector window opens, select the Observational Spectra Services, and again tick the 'International Ultraviolet Explorer'.
27. Click the red 'Query' button.

28. The spectra are then loaded into the region in the lower part of the main VOSpec window. Sort the table by distance by clicking on the column header called 'Distance (degrees)'. This distance is the difference between the coordinates of the object, given in the Ra (right ascension) and Dec (declination) fields at the top of the VOSpec window, and the coordinates associated to each spectrum (e.g. where in the sky the telescope was looking). The smaller the distance, the closer the spectrum was obtained to the centre of the galaxy.

International Ultraviolet Explorer

To retrieve	Name	Distance (degrees)	ssa:dataset.datamodel
☐	swp29939mxlo, 3C 273	5.275756347752625E-4	Spectrum-1.0
☐	swp29940mxlo, 3C 273	5.275756347752625E-4	Spectrum-1.0
☐	swp25973mxlo, 3C 273	5.275756347752625E-4	Spectrum-1.0
☐	swp25974mxlo, 3C 273	5.275756347752625E-4	Spectrum-1.0
☐	swp23063mxlo, 3C 273	5.275756347752625E-4	Spectrum-1.0
☐	swp23064mxlo, 3C 273	5.275756347752625E-4	Spectrum-1.0

29. Choose some of the spectra with distances of ~5.276E-4 and beginning with the name 'swp' (from the Short Wavelength spectrograph of the International Ultraviolet Explorer, in the wavelength range 0.115 to 0.198 microns). Then click the 'RETRIEVE' button:

30. The spectra are again displayed in the main VOSpec window.
31. Again, change the display from points to lines, and click on the 'View' button.
32. Find the central wavelength of the strongest emission line (the line to the left). It may help to zoom into the line. Place your cursor in the centre of the peak of the line and make a note of the wavelength value which is displayed in the bottom left of the VOSpec window, below the 'View' button.
33. Calculate the redshift of the galaxy using the following equation:

$$z = \frac{\lambda_{obs} - \lambda_{emit}}{\lambda_{emit}}$$

where z = redshift, λ_{obs} = the observed wavelength (the wavelength you just measured in point 32), and λ_{emit} = the emitted wavelength.

34. Make a note of λ_{obs} and the redshift you calculate for 3C 273:

NAME	λ_{obs}	z
3C 273		

35. To check that if this redshift is correct, go to the following website: http://ned.ipac.caltech.edu/forms/byname.html . This website is the NASA/IPAC

Extragalactic Database (NED), which is used by professional astronomers to search for data on all types of extragalactic objects (i.e. objects outside our galaxy). Type '3C 273' into the Object Name field and click the 'Submit Query' button. In the results page the redshift of the object is given in the 'SOURCE LIST' box. For 3C 273, z=0.158339.

36. Go back to the main VOSpec window and change the 'RedShift' value from 0.00 to 0.158339 (located on the left-hand side, below the Flux Unit field). Tick the box to the right of the RedShift field and watch the wavelength values on the x-axis adjust. We now see the strong Lyman alpha emission line located exactly at its rest wavelength of 0.121567 microns.
37. We are now going to search for the Lyman alpha emission line from a quasar galaxy with a larger redshift. In the Target field type '**3C 186**', keep the Size value as 0.1 and click the 'Query' button. And remember to untick the 'Redshift' box!
38. When the Server Selector window opens, this time select the Observational Spectra Service called 'Hubble Space Telescope Faint Object Spectrograph'.
39. Click the red 'Query' button.

40. Two spectra load into the table view field. Select both spectra and click the 'RETRIEVE' button.
41. The spectra are displayed in the main VOSpec window and are in the wavelength ranges ~0.22 microns (ultraviolet) to 0.48 microns (visible).
42. Again, change the display from points to lines, and click on the 'View' button.
43. Find the central wavelength of the strongest emission line (the line to the left). It may help to zoom into the line. Place your cursor in the centre of the peak of the line and make a note of the wavelength value which is displayed in the bottom left of the VOSpec window, below the 'View' button.
44. Calculate the redshift of the galaxy using the equation given above and make a note of the values:

NAME	λ_{obs}	z
3C 186		

45. You can check if your redshift value is correct by looking on the NASA/IPAC Extragalactic Database website (repeating steps 35 and 36).
46. Repeat steps 37 to 45 for 3 more quasars, called **PKS 1127-14** (this quasar is also called [HB89] 1127-145), **3C 286** and **3C 298**. For 3C 298, choose either of the two Hubble Space Telescope Faint Object Spectrograph spectra (notice that there are many narrow absorption lines mixed within the broad Lyman alpha emission line). For 3C 286, choose the Hubble Space Telescope Faint Object Spectrograph spectra beginning with the names 'y2b10b...' (Lyman alpha is the strongest emission line). And for PKS 1127-14, choose the Hubble Space Telescope Faint Object Spectrograph spectrum called 'y12b0602t, PKS1127-14', and make a note of λ_{obs} and the calculated redshift:

NAME	λ_{obs}	z
PKS 1127-14		
3C 286		
3C 298		

47. Repeat the same steps for two more quasars, with even larger redshifts, where the Lyman alpha emission is redshifted from the ultraviolet into the visible part of the electromagnetic spectrum:
48. In the Target field type '**[HB89] 1143-245**' (this quasar is also called PKS 1143-245), keep the Size value as 0.1 and click the 'Query' button. And remember to untick the 'Redshift' box!
49. This time, when the Server Selector window opens, select the Observational Spectra Service called 'ESO Spectrum Service'. This service contains spectra from the ground based telescopes of the European Southern Observatory (ESO).
50. Click the red 'Query' button.

Note:

- If you are unable to load the ESO Spectrum Service in VOSpec, download spectra for the two objects here, and then load them into VOSpec (File -> Open Spectrum):
- http://www.rssd.esa.int/SD/ESAVO/docs/HB89-1143-245_UV_SFLX_212044_2006-01-30T05_27_50.115_BLUE390D1_2X2_10.xml
- http://www.rssd.esa.int/SD/ESAVO/docs/HB89-0237-233_UV_SFLX_112204_2001-11-22T05_06_55.318_BLUE437D2_2X2_10.xml

51. Many spectra appear this time in the table view field. Expand the Name column. All of the spectra start with 'UV...' in the name, this doesn't stand for ultraviolet, but instead for 'UVES' which is the name of one of the spectrographs at ESO. The name also contains the dates that the spectra were observed, and the central wavelengths of the spectra, for example '...REDL769...' '...BLUE437...' Try loading a few of these and see how they all lie in different wavelength regions.

52. Select the spectra that contain the name '...BLUE390...' and click the 'RETRIEVE' button.

53. These are very high resolution spectra with many narrow absorption lines. Also observable is a very broad emission line towards the left of the spectrum, near 0.36 microns (the Lyman alpha line).

54. Find the central wavelength of this line and calculate the redshift:

NAME	λ_{obs}	z
[HB89] 1143-245		

55. You can check if your redshift value is correct by looking on the NASA/IPAC Extragalactic Database website (repeating steps 35 and 36).

56. Repeat steps 48 to 56 for the quasar called **[HB89] 0237-233** (this quasar is also called PKS 0237-233), select one of the European Southern Observatory spectra with the name containing '...BLUE437...', and make a note of λ_{obs} and the calculated redshift:

NAME	λ_{obs}	z
[HB89] 0237-233		

57. **Additional:** Make a Hubble diagram. The Hubble Distances of galaxies can be found in the NED database, and are given below. Add your redshifts to the table and make a Hubble diagram of Distance (in Mega parsecs, Mpc) versus Velocity, v, (in km/s), where redshift, $z = v/c$.

NAME	***z***	***v* (km/s)**	***Hubble Distance (Mpc)***
3C 273			655
3C 186			4384.1
PKS 1127-14			4867.4
3C 286			3491.3
3C 298			5906.1
[HB89] 1143-245			7971.9
[HB89] 0237-233			9126.7

Do you see a linear relationship between velocity and distance?

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