STARS RESOURCES

Student workbook

Make your own spectroscope

ACTIVITY

Conduct spectroscopy experiments using a simple spectroscope.

BACKGROUND INFORMATION

Spectroscopy is one of the most important tools in astronomy. Astronomers can't go out into space and collect physical samples of stars, planets, gas, or dust. Instead, they rely on collecting the light that celestial objects emit.

After the light is collected using a telescope, it is analysed. First, the light is split up into its component colours to create a spectrum (plural: spectra). Second, the specific wavelengths of light which are present or absent are identified. Finally, the light is analysed to determine the importance of those particular wavelengths.

ASTRO 3D astronomers use spectroscopy to determine how fast a distant object is travelling through space, the direction in which it is travelling, its chemical composition, its density, and its temperature.

Astronomical spectroscopy is performed using light from all parts of the electromagnetic spectrum (gamma rays to radio wavelengths, see Figure 1).

This activity focuses on UV through to infrared wavelengths. There are a few reasons for this:

1. It is easier to build detectors and mirrors/lenses for these wavelengths using modern materials;
2. Much fundamental and interesting science can be studied using these wavelengths;
3. At such small wavelengths (in the order of nanometres in length), spectroscopes can be built quite small (i.e. small enough to be transported easily).

BACKGROUND INFORMATION cont'd

EM spectrum

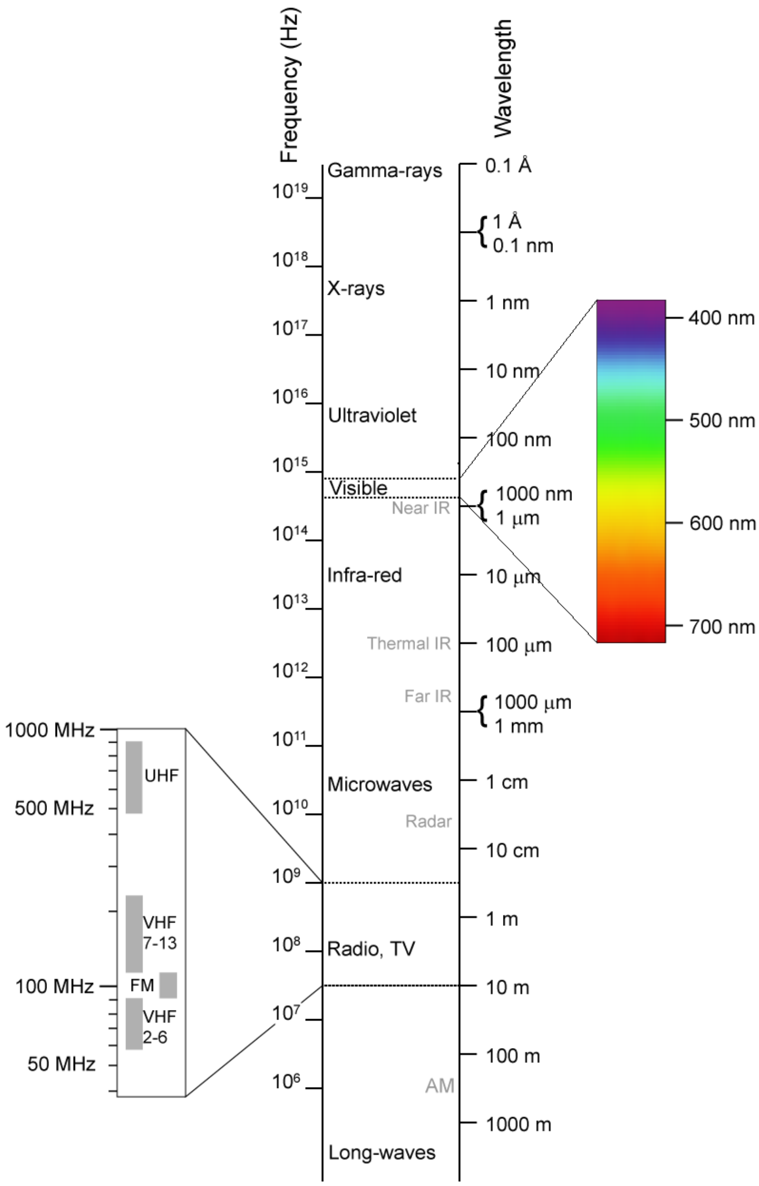

Figure 1: Electromagnetic Spectrum, spanning gamma-rays to radio (By transferred by Penubag (talk · contribs) on 05:04, 15 May 2008 - taken from en.wikipediaen:Image:Electromagnetic-Spectrum.svg and en:Image:Electromagnetic-Spectrum.png (deleted), CC BY-SA 2.5, https://commons.wikimedia.org/w/index.php?curid=4051422)

BACKGROUND INFORMATION cont'd

There are a few ways in which light is produced.

The most common process is from electronic transitions by the electrons in the outer shell of the atom (also known as the valence electrons).

Take hydrogen, for example.

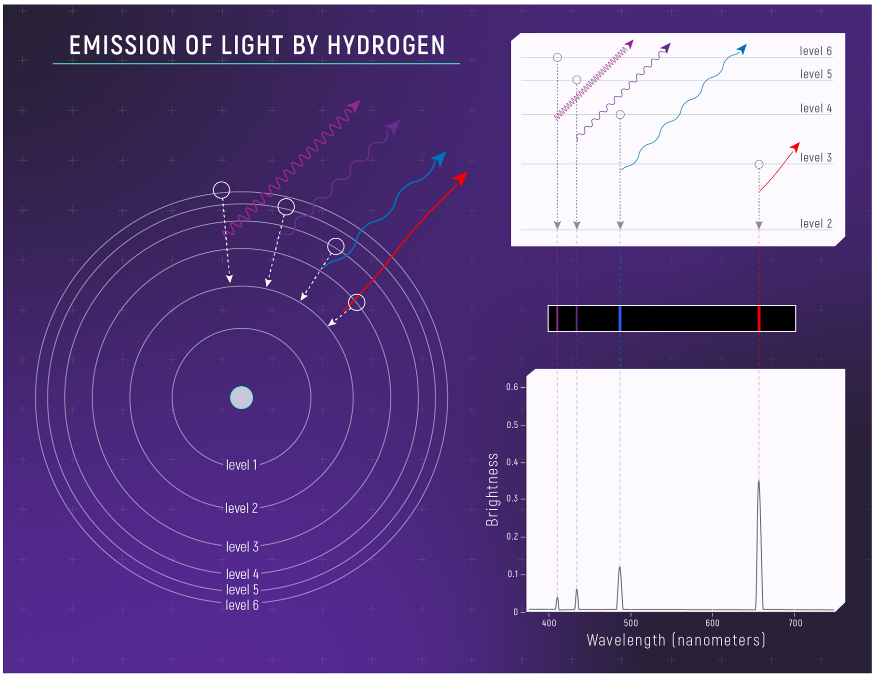

Figure 2: The relationship between a hydrogen atom and its emission spectrum. (Left) A simple model of a hydrogen atom showing four of the many possible "drops" the electron could make when it emits light. (Right) The relationship between the electron drop and the specific wavelengths of light that the atom emits. When an electron drops down from one energy level to another, it emits a very specific wavelength of light (i.e., it emits a photon with a specific energy). The farther the drop, the shorter the wavelength and the higher the energy of the photon. Wavelengths that are emitted appear as bright lines in the spectrum. This illustration shows a set of drops that correspond to the emission of visible wavelengths (the Balmer Series). (taken from webbtelescope.org)

If the electron in the hydrogen atom absorbs a photon of light, it can jump up to a higher energy state (Figure 2).

After a while, the excited electron falls back down to the lower energy state and releases a photon of light.

The amount of energy contained by the photon is specific to the size of the jump.

BACKGROUND INFORMATION cont'd

This electronic process happens for all atoms, but the sizes of the gaps between levels are unique for every element on the Periodic Table via the equation E=hf where E is energy, h is Planck's constant ,and f is frequency.

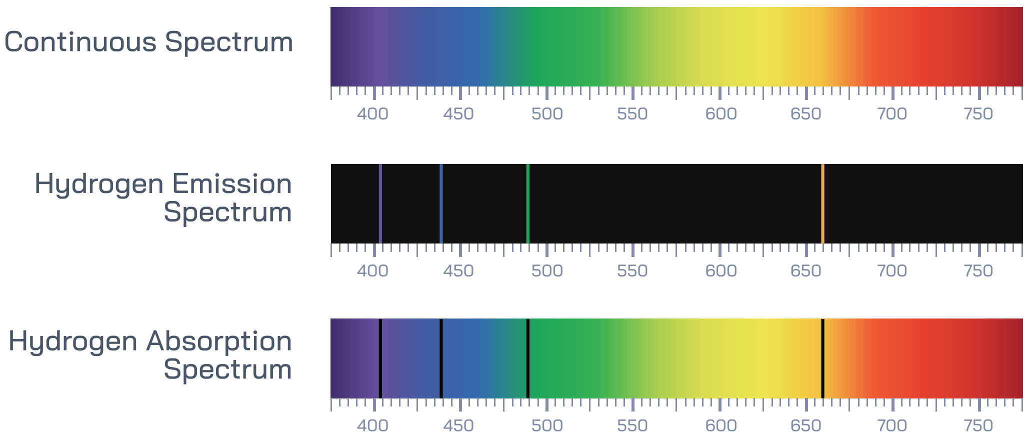

Figure 3: The pattern of light colours and dark patches that are characteristic for hydrogen. Hydrogen has the most simple spectrum of all of the elements on the Periodic Table. Credit: Adobe Stock

Types of spectroscopy

Astronomers can identify elements from the presence of light (emission) or its absence (absorption) (Figure 4).

Emission

When a celestial object releases light, and we collect it, it's referred to as emission spectroscopy. The advantage is that you can see the specific light that you're looking for, but it can also be fainter and more difficult to actually locate where in the sky it came from.

Absorption

If a celestial object releases light, but an object in front of it absorbs some of that light, it's referred to as absorption spectroscopy.

BACKGROUND INFORMATION cont'd

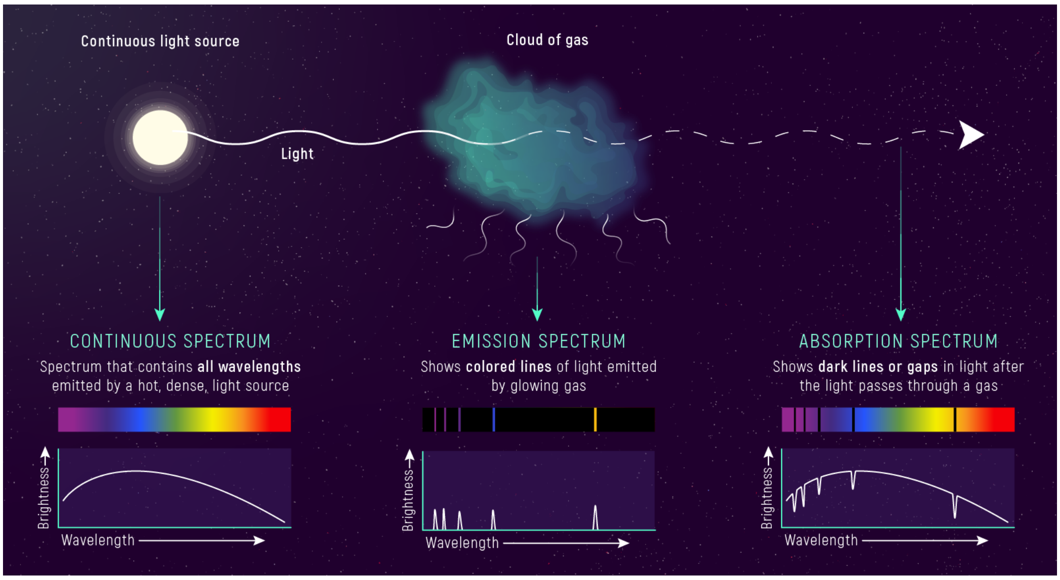

Figure 4: When light passes through a cloud of gas, light at specific wavelengths excites atoms in the cloud. These are seen as absorption lines, obvious by their lack of colour, at those wavelengths in the spectrum of the source. Sometime later, the atoms de-excite and emit light at these wavelengths, but this light is emitted in all directions, as shown in the figure above, and are seen as emission lines. (Credit: webbtelescope.org.)

The puzzle

Once the light is collected, how do we measure its wavelength? Do we need a ruler? Do we weigh it?

First of all, light is collected by a telescope. That light is then passed through a specialised instrument called a spectrograph (sometimes referred to as a spectroscope or a spectrophotometer).

The spectrograph is where the 'magic' happens. It is a highly specialised machine designed to spread the light. This is usually performed using a grating or a prism (or sometimes both, called a 'grism'). The device that the students will make uses a transmission grating (reflection gratings also exist); where the light travels through a piece of transparent material and splits it up as it encounters the tiny slits ruled into the material.

The spread-out light is focused onto special detectors (Figure 5), like those on any digital camera. The detectors, though, can't detect colour; their specialty is knowing how much energy hits them.

BACKGROUND INFORMATION cont'd

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'Colour' measurements require a bit of trickery.

1. Light spreads out in a predictable manner. Scientists have long known how to calculate the behaviour of each wavelength as it encounters a diffraction grating. They use the equation:

$$d \sin \theta = m\lambda$$

2. A detector is made up of millions of pixels. With a bit of maths, and trial and error, detectors can be precisely placed to detect all of the shades of red, all of the shades of blue, and so on.

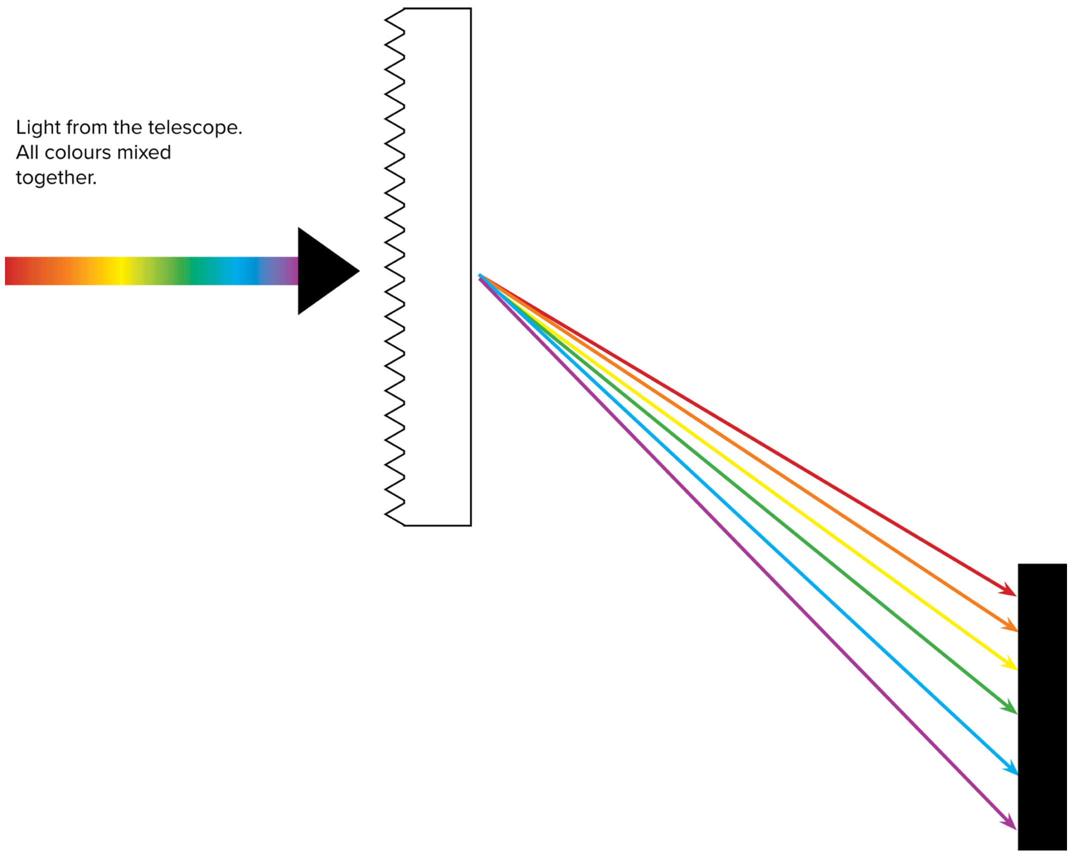


Figure 5: A transmission grating. Light splits up as it travels through the grating, and then falls on the detector. (Credit: Lara Sharp)

BACKGROUND INFORMATION cont'd

Interpreting spectra

Astronomers look at the colours of light that are received, and can determine what elements or molecular species must have created or absorbed that light. But how can they be so certain?

During the 20th century, astronomers used tubes of gas (e.g. hydrogen, neon, argon). When the gas was heated up, it gave off characteristic colours which the scientists could analyse using benchtop spectrometers. Over time, more complicated equipment was developed. This equipment probed elements, ions or molecules to increasingly greater levels of detail, and under varied conditions (e.g. varying pressure and temperature). Although these experiments were extremely useful, they had limitations because it is very difficult to reproduce on Earth the entire range of density and temperatures in the Universe (from cold, vacuum of space to the hot, dense interior of stars).

DID YOU KNOW?

Electronic transitions (Figure 6) are only one process for creating spectral lines. The other two important processes are vibrational and rotational emission. When the bonds between atoms stretch and waggle about, photons are created at predictable, quantized, energy levels. These energies are often significantly lower than those of electronic transitions (infrared to radio wavelengths; >10,000nm). Together, electronic transitions, vibrational and rotational bands encompass X-ray right through to the radio wavelengths of the electromagnetic spectrum.

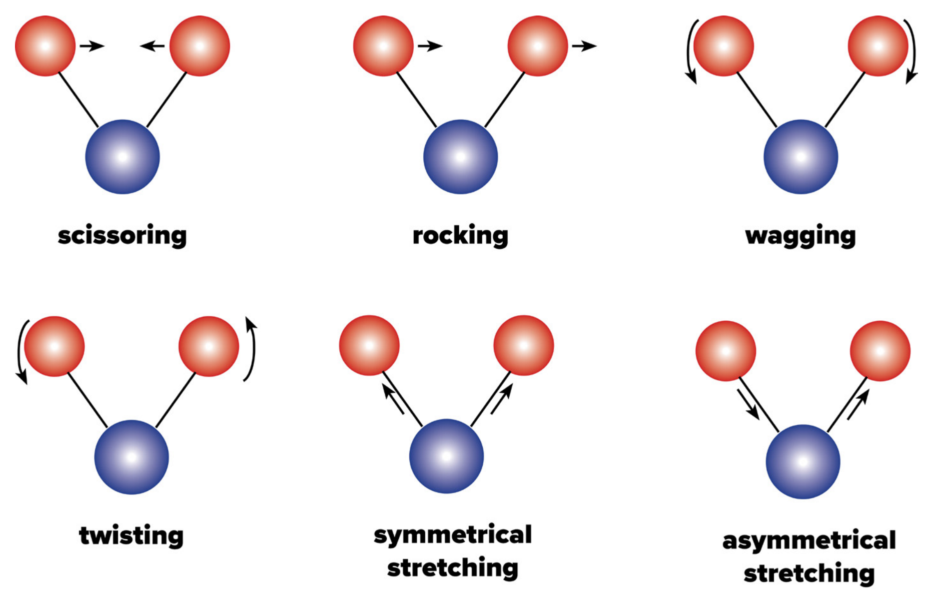


Figure 6: So-called roband transitions. When atoms move about on their bonds within molecules, they absorb and emit light. These 'colours' are well known and linked to specific motions. Credit: Lara Sharp

BACKGROUND INFORMATION cont'd

FEATURE – Thomas Nordlander

Dr Thomas Nordlander is an astronomer with ASTRO 3D, based at the Australian National University in Canberra. He creates synthetic spectra to unravel fine detail about the evolution of our galaxy and the stars that it contains.

But why does he create synthetic spectra on a computer when laboratory-based ones already exist?

Because the Sun can't be recreated in a lab.

Picture our Sun. Its atmosphere is 100 kilometres thick, and is hot (around 4000 degrees C). From observations of the Sun, astronomers have found about 1,000,000 spectral lines. Laboratory experiments can match up with about 100,000 of those lines: half of them are from iron and the other half are mostly unidentified.

And now picture a star which is completely different to our Sun – larger, hotter, older or younger, further away...the potential library of spectral lines is seemingly endless!

Additionally, these spectral lines are absorption lines, rather than emission lines. This is how it works: The interior of the Sun is extremely hot, and emits a black-body continuum (i.e. no spectral lines being produced). Further out, the temperature is lower. This cooler material absorbs radiation from the internal black-body emission, creating dips or gaps that we see as absorption lines.

These extreme and changeable conditions lead to even more spectral lines than we might otherwise expect, and influence where those lines might appear.

Thomas can make reliable estimates of what elements, ions or molecular species created those lines by creating a computer model. This model relies heavily on existing laboratory data (known as empirical data), and then adds in other factors such as:

- temperature,
- thickness of the atmosphere,
- how many atoms would be excited,
- the possible ionisation states of atoms/molecules/ions,
- the density of a star's atmosphere,

BACKGROUND INFORMATION cont'd

- convection (i.e. flow of gases due to temperature variations) within the atmosphere,
- how easily the photons can travel through the atmosphere (known as opacity),
- and more.

The spectra that Thomas creates benefits the astronomical community across the world. As is tradition amongst academics and research scientists, he shares his results and computer code through publishing research papers, and using online platforms such as GitHub.

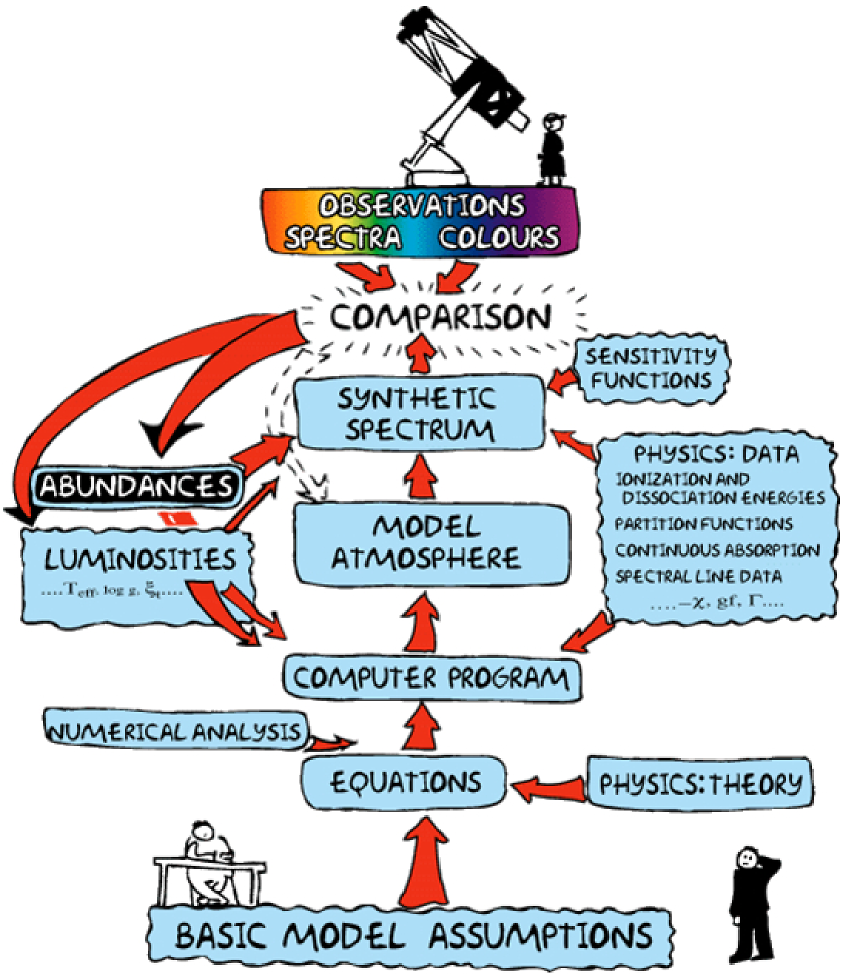


Figure 7: By Bengt Gustafsson - Bengt Gustafsson, Astronomical Observatory, Uppsala, CC BY-SA 3.0, https://en.wikipedia.org/w/index.php?curid=23396538

BACKGROUND INFORMATION cont'd

Astronomical absorption spectroscopy

It's all well and good to have a library of both laboratory spectra and synthetic spectra, but astronomical light sources are complicated and almost never pure.

Benchtop spectroscopy, the sort that would happen in a laboratory (Figure 8), is a highly controlled set-up. It's possible to characterise the light source, and subtract its light from the absorption spectrum.

Laboratory absorption spectroscopy

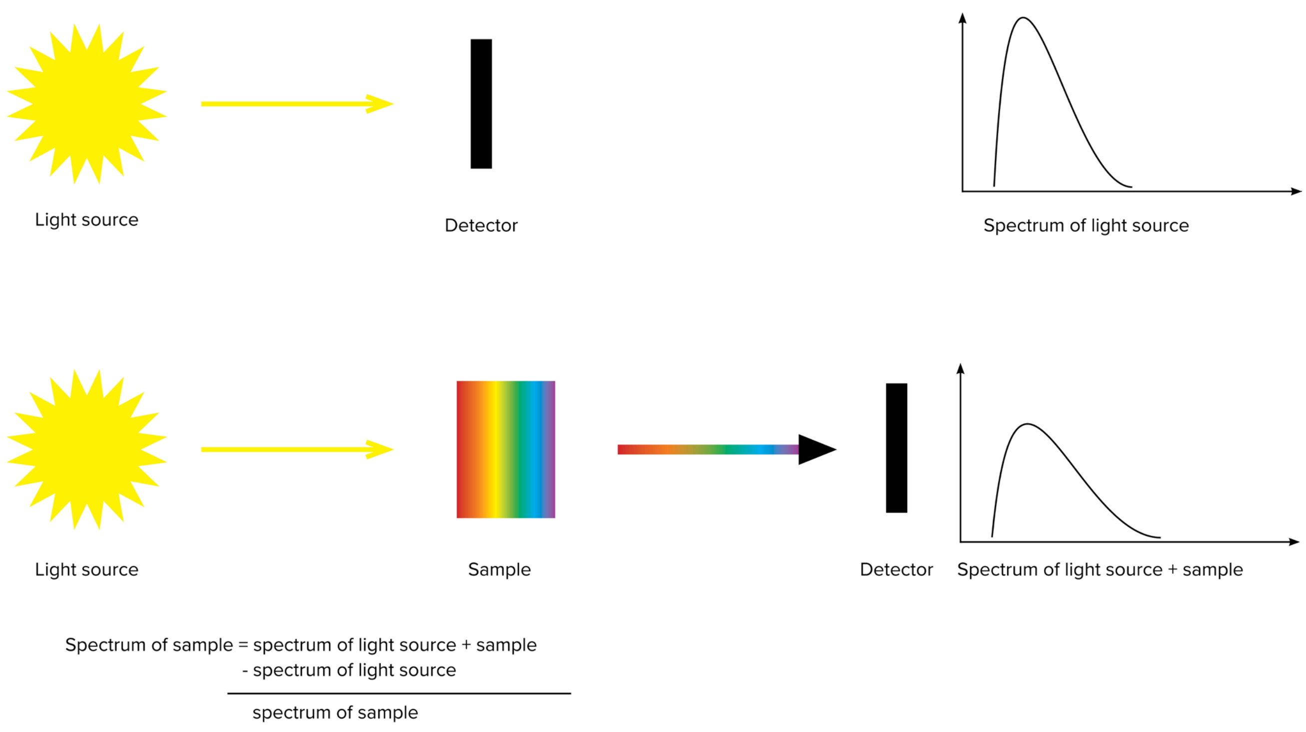
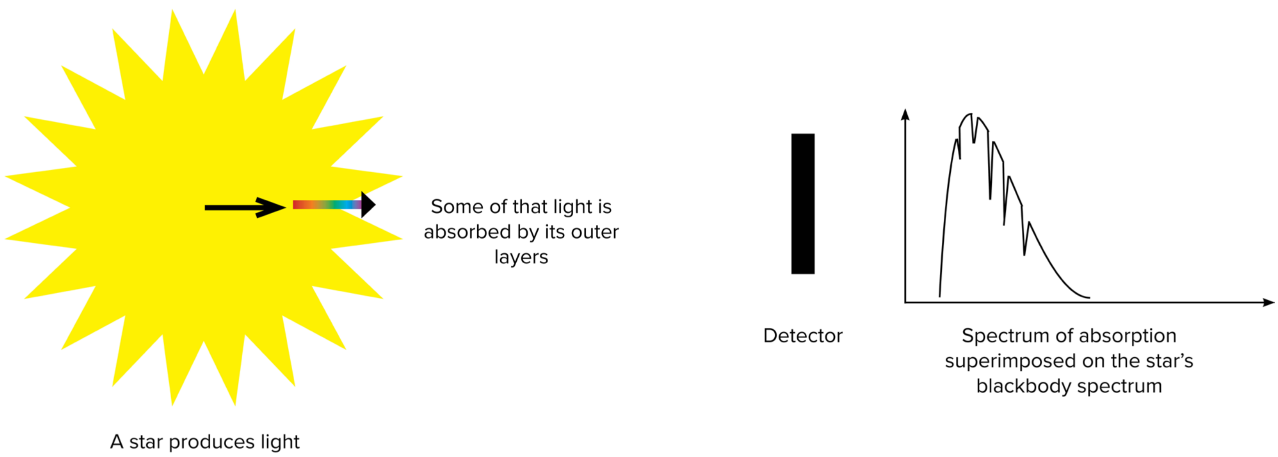


Figure 8: In a laboratory the spectrum of a light source is relatively easy to obtain. Credit: Lara Sharp

BACKGROUND INFORMATION cont'd

When looking at a star, it's not possible to experimentally isolate the star's output and separate it from the absorption that is happening in its atmosphere. Instead, any spectrum from a star is the blackbody curve with absorption features (dips) superimposed on to it. (Figure 9)

Astronomical absorption spectroscopy



Absorption spectrum of star = emission spectrum of light source + absorption spectrum of outer layers
- effects of absorption in Earth atmosphere
- Earth's sky brightness
x smoothing factors

absorption spectrum of star

Figure 8: Analysing the light from a star is complicated by processes going on within the star, and by other environments the light may have travelled through before reaching our telescopes. Credit: Lara Sharp

BACKGROUND INFORMATION cont'd

Let's look at spectra of two different galaxies and see what science they reveal. What do you see?

The first thing to notice is that one spectrum shows lines going upwards from zero, while the other one has dips from above. This tells us that one is an emission spectrum and one is an absorption spectrum.

The second thing to notice is the number of peaks or dips, and their positions, on each spectrum.

Figure 9 shows an emission spectrum. It contains lots of peaks, some of which are stronger than others. What does this combination of peaks tell us?

• The large peak at 656nm corresponds to the electron in a hydrogen atom being excited to the third level and falling to the second lowest level (n=3 -> n=2) (Figure 9). This happens in hot hydrogen gas which is heated by short-lived, massive stars in galaxies. These young stars are part of stellar nurseries where many new stars burst into being.

• The ratio in strength between different ionisation states of oxygen (single- versus double-ionised, denoted as OII and OIII, respectively), shown by peaks at 372nm and 500.7nm, tell a story about the temperature. The more electrons have been ripped off (i.e. the more highly ionised the atom), the higher the temperature.

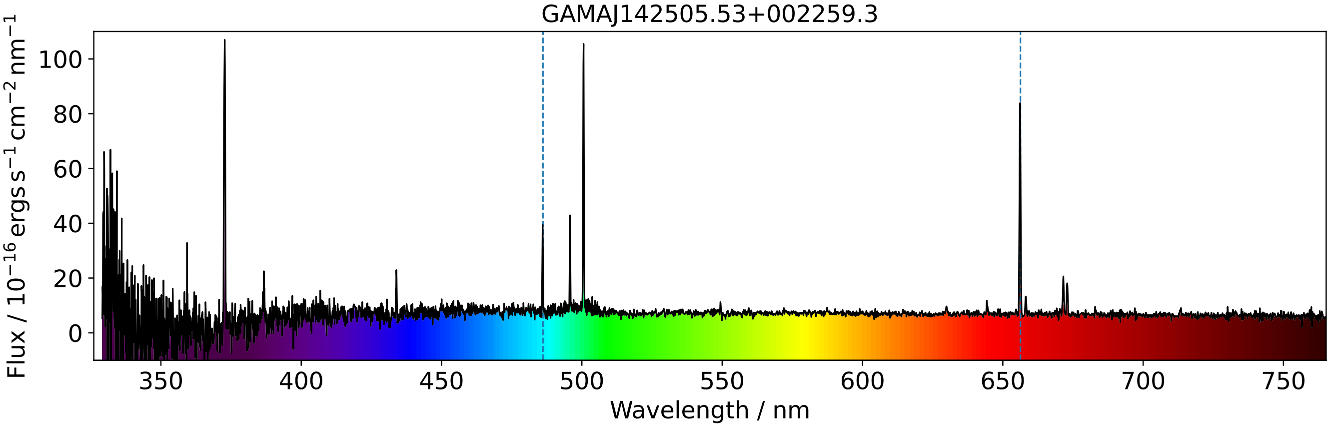


Figure 9: Emission spectrum from an active galaxy which is forming new stars. The dotted lines show where the two stong hydrogen lines should be. Credit: Sven Buder

BACKGROUND INFORMATION cont'd

The second spectrum in Figure 10 is an absorption spectrum. It shows most colours relatively brightly, but in a few places there are dips where those colours have been absorbed by something (perhaps gas). The other thing to notice is the lack of a strong hydrogen line at around 650nm (the dotted line shows us where the dip would be if it was present).

The lack of a line at around 650nm indicates that there is no star formation happening here. Only massive, short-lived stars are energetic enough heat up surrounding hydrogen gas to produce lines at 650nm. This region of space is likely to be old and cooler.

The predominance of absorption lines suggests that there is something creating the light, and something else absorbing it. The something else could be the outer layers of a star or clouds of gas or dust between stars.

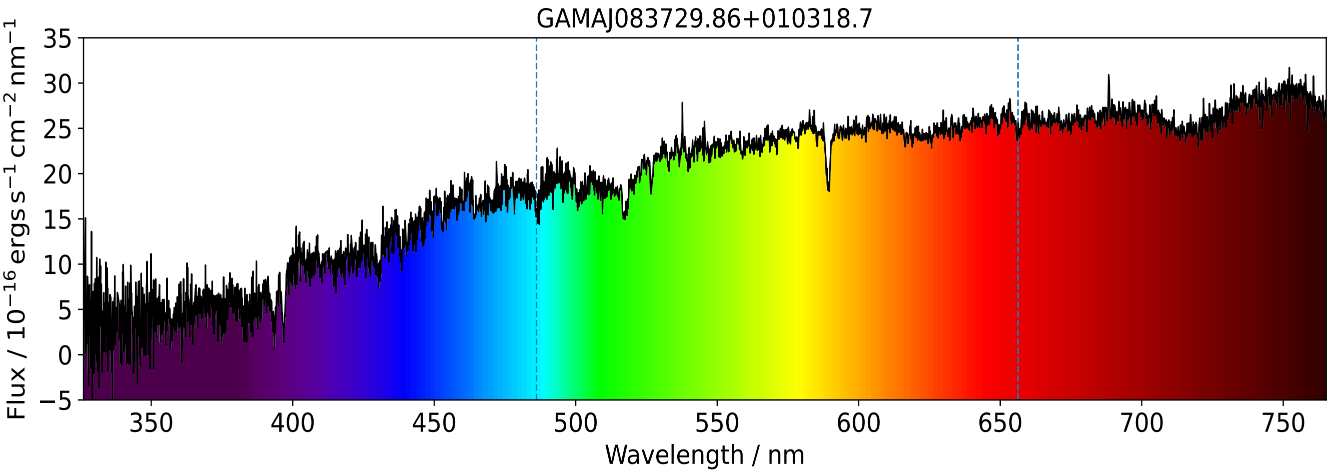


Figure 10: Absorption spectrum from an old galaxy. The dotted lines show where the two stong hydrogen lines should be. Credit: Sven Buder

This example is just the tip of the iceberg of stories that can be told through astronomical spectra. Other stories use calcium lines as indicators of the age of a galaxy, because only older stars create calcium. Some lines give information about the density of a galaxy; yet others are the first step in calculating the strength of gravity on the surface of stars.

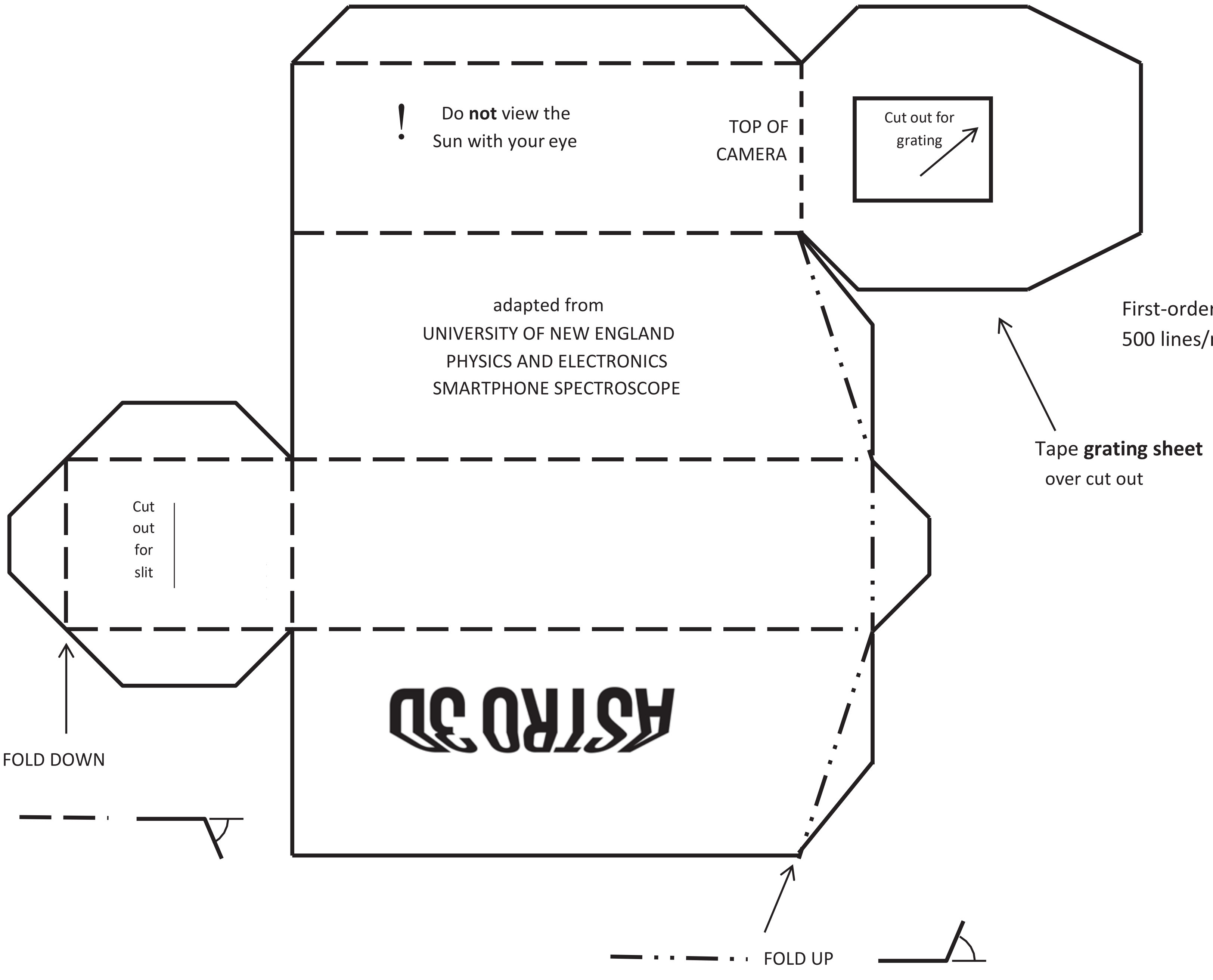
EQUIPMENT

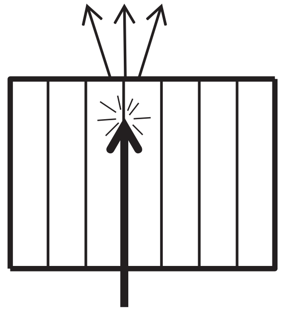
You will need the following to complete this activity:

- the A4 spectroscope template (see below),
- a pair of scissors,
- sticky tape,
- a piece of diffraction grating (purchase from Edmund Optics https://www.edmundoptics.com.au/p/12700-linesinch-6quot-x-12quot-sheets-2pack/11226/)
- light sources
- food dye/water/drinking glass
- dilute cola/water/drinking glass (dilute until solution is the colour of apple juice)
- pen/pencil
- smartphone or digital camera or tablet camera (optional)
- notebook

EXPERIMENT

1. Build your spectroscope following the instructions on the template. Be careful to not put fingers prints on the grating. Gratings are delicate, and can't be washed or wiped. https://youtu.be/ZQGIITZ2sno





First-order diffraction 18° at 600 nm
500 lines/mm 25 x 34 mm grating

Smartphone Spectroscope
Ron Bradbury
Physics and Electronics
University of New England
Armidale NSW

Materials:

- This sheet printed on 160gsm dark coloured paper
- Diffraction grating sheet Edmund Optics 54.509, cut long side in nine pieces each 34mm, cut short side in six pieces each 25mm
- Sticky tape

Tools:

- Scissors
- Smartphone or tablet, with built-in camera

Method:

- Cut out spectroscope on solid line
- Cut a 1mm slit (or as small as possible) where indicated.
- Fold up spectroscope such that black surface is inside and fix with tape
- Fix diffraction grating over hole with sticky tape
- Place grating onto smartphone camera lens

Use:

- Point slit toward light source (fluorescent tube etc.)
- Adjust camera zoom
- View spectrum on smartphone

Warning: Do not view the sun with your eye

For further details and an instructional video see: https://astro3d.org.au/education-and-outreach/diy-smartphone-spectroscope/

EXPERIMENT cont'd

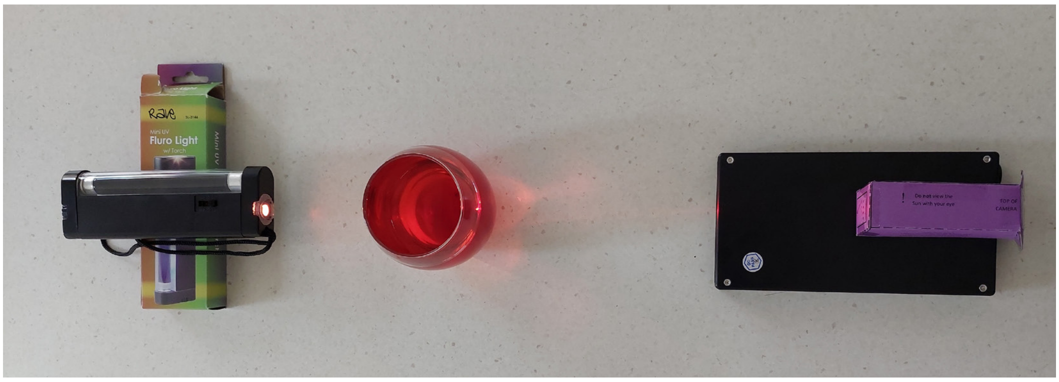
2. Now try out your spectroscope. Point the slitted end at a light source. Place your eye at the grating end (while trying not to touch it with your cheek or eye). You may need to shift your head a little to the left or right to see the rainbow inside the spectroscope.

3. Use your spectroscope to observe the light sources in the classroom, or ones that your teacher has set up for you. ** Follow all safety precautions as outlined by your teacher. Do not look directly at the Sun OR lasers with any device or with your naked eye. **

4. In your notebook, note the main colours that you can see for each source. If you can see the entire rainbow, then use the word 'continuum'. Note if some colours are dampened (i.e. weaker).

5. If you have access to a camera, take a photo down the spectroscope. It takes a bit of practice to keep the camera steady. Record in your notebook the name of the light source and its corresponding photo filename for future reference.

6. Now explore absorption. A solution of food dye in water has been set up in front of a white light source. Look at the white light source with your spectroscope. Record what you see. Next, move the glass full of food dye in front of the light, and use your spectroscope to see the light that has passed through the dye. Record what you see and note any changes between the two set-ups.



RESULTS

Light source	Main colours observed	Extra comments or observations

Light source	Filename

FOLLOW-UP QUESTIONS

1. Define these words:

a) spectrum

b) spectrograph/spectroscope

c) spectrogram

2. If you compare the colours you can see through your spectroscope with your eye, to the colours/number of lines you can see in the photograph, are there any differences? Why do you think that might be?

FOLLOW-UP QUESTIONS

3. If you observed a spectral lamp, or the Christmas lights, do you see unexpected colours of light through your spectroscope? What might be the source of these colours? And what steps might you conduct to exclude that light?

4. How do you think astronomers remove unwanted light?

5. Before digital sensors like CCDs existed, how do you think astronomers recorded the intensity of light? Read this article to find out more: https://onlinelibrary.wiley.com/doi/full/10.1002/asna.20230066

FURTHER RESOURCES

"How does astronomy use the electromagnetic spectrum?", Space.com website, https://www.space.com/electromagnetic-spectrum-use-in-astronomy, 22 April 2023

"Hubblecast 126: From Ultraviolet to Infrared: Comparing the Hubble and James Webb space Telescopes", https://esahubble.org/videos/hubblecast126a/ (4:47 mins), Dec 2019

"DIY Smartphone Spectroscope", ASTRO 3D website, https://astro3d.org.au/education-and-outreach/diy-smartphone-spectroscope/

"Types of Astronomical Spectra", CSIRO Australia Telescope National Facility, https://www.atnf.csiro.au/outreach/education/senior/astrophysics/spectra_astro_types.html

"Spectroscopy explained – with Crooked Science and USyd Kickstart", PhysicsHigh YouTube channel, https://youtu.be/cMCzA9rqJy8?si=4G4jLJS8cv5SZLCE (21:03 mins), April 2019

"Stellar Spectroscopy – what can we learn about stars", PhysicsHigh YouTube channel, https://youtu.be/oM5lEG2woA0?si=ISpHMOjhOlnStjuE (16:44 mins), April 2019

"Spectroscopy, explained", NASA Goddard Youtube channel, https://youtu.be/_1mpHBAXh1c?si=WuaBXD5Mc5C8p2Yq (7:52 mins), Aug 2023

"How do we know what air is like on other planets?", minute physics YouTube channel, https://youtu.be/UfJ-i4Y6DGU?si=887ePqSforBD5Hpg (2:42 mins), Feb 2016

"Spectrum Demo: Continuous and Emission", Physics Demos YouTube channel, https://youtu.be/oae5fa-f0S0?si=awb5MhxRwOogKb4U (6:30 mins), Aug 2016

Atomic Spectra Database, NIST, https://www.nist.gov/pml/atomic-spectra-database

"How space telescopes break down light?", Hubble Space Telescope YouTube channel, https://youtu.be/5P03cvh_aHQ?si=EWuhDEv22jtBip4W (1:37 mins), May 2019

All resources accessed May 2024.

Thanks to Drs Sven Buder, Andrew Battisti and Thomas Nordlander for their scientific and educational advice, diagrams and profiles.