



## 6.1: Identifying Absorption Lines in Blue Sky and Solar Spectra

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### ABSTRACT

Spectroscopic analysis is one of the cornerstones of astronomical research. By observing how the spectra of different astronomical objects behave, we can make grand conclusions about the nature of our universe. Even the spectrum of the blue sky is full of minute details which can ultimately hint at the composition of the atmosphere and the sun. In this lab, we will make spectroscopic measurements of the blue sky and the sun. We will then identify different absorption lines within our spectra to infer the composition of gases in the atmosphere and elements in the solar chromosphere.

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- Never look directly at the Sun with the naked eye or with an optic (unless you have the proper solar filter). Permanent and irreversible eye damage may result.
- Never use your optic to project an image of the Sun onto any surface. Internal heat build-up can damage the optic and any accessories attached to it.
- Never leave your optic unsupervised. Make sure an adult who is familiar with the correct operating procedures is with your optic at all times, especially when children are present.



# 1 Introduction

## 1.1 Spectrum

At this point in your physics education, you've probably noticed that electromagnetic waves are quite important. Our interest in electromagnetic radiation will only go up from here. After all, the universe is an extensive laboratory, but where most of it just lies too far away. As a result, observational astronomers have historically investigated the universe using light (with some exciting new mediums arising in the past decades!). Interrogating electromagnetic radiation can tell us about compositions, local movements, global kinematics, and about matter that *can't* be seen. Light has always been the language in which the universe communicates with us.

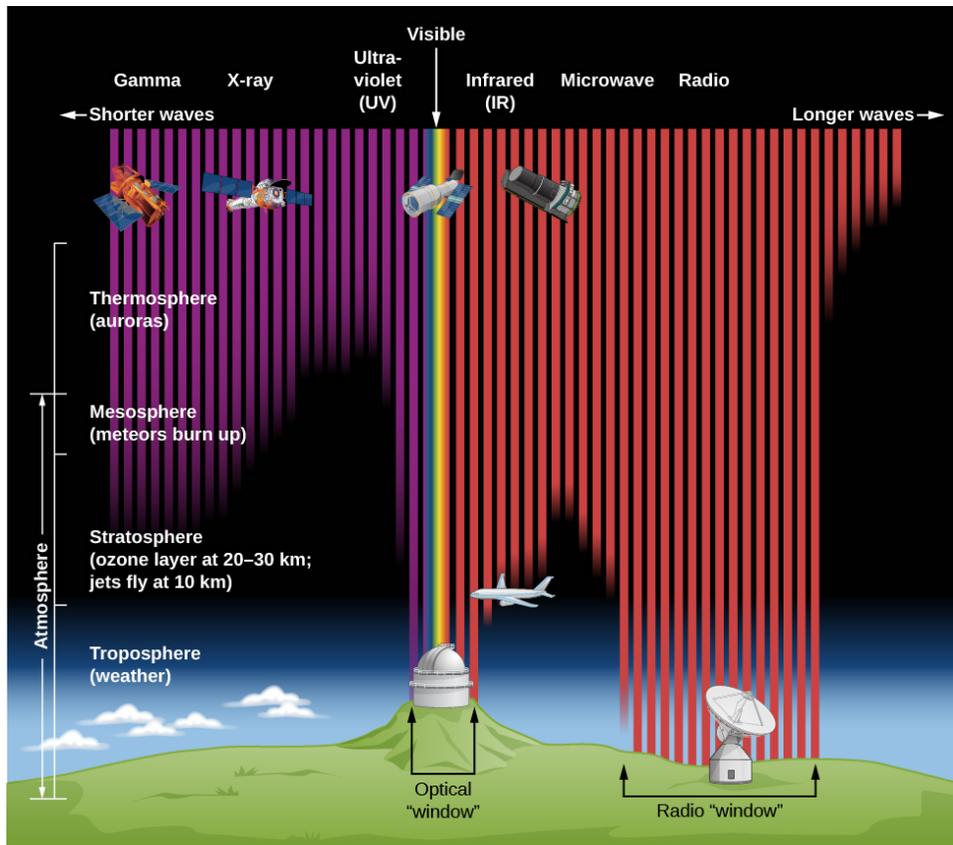
You might be aware that light, or electromagnetic radiation, has both wave and particle characteristics. For a review on how light behaves, please see pages 145–156 from Openstax Astronomy<sup>1</sup>. The properties of electromagnetic radiation change dramatically with light's wavelength. Human eyes are adapted to perceive light of a small range of wavelengths (380–700 nm), and depending on the wavelength(s), our brains interpret it as a particular colour. We can't 'see' light outside this range, but that doesn't mean we don't interact with it. For example, we use radio waves ( $\sim 30$  cm–10,000 km) to transmit information throughout the globe. Microwaves ( $\sim 30$ –0.03 cm) enable the telecommunication infrastructure and warm up our food. UV rays ( $\sim 100$ –400 nm) are invisible but can still cause sun burns. Gamma rays ( $\lesssim 100$  pm) are used in radiotherapy and for sterilisation purposes. Figure 1 shows light of different wavelengths entering Earth's atmosphere, and how well the atmosphere transmits (lets it through).

One of the most important questions we can ask about an astronomical object is how much light of a particular wavelength it emits for a range of wavelengths. This distribution is called a **spectrum**. Astronomers have and continue to use spectra in a variety of clever ways to figure out properties for objects. In this lab, we'll be observing the spectrum of the bright blue sky as well as the sun.

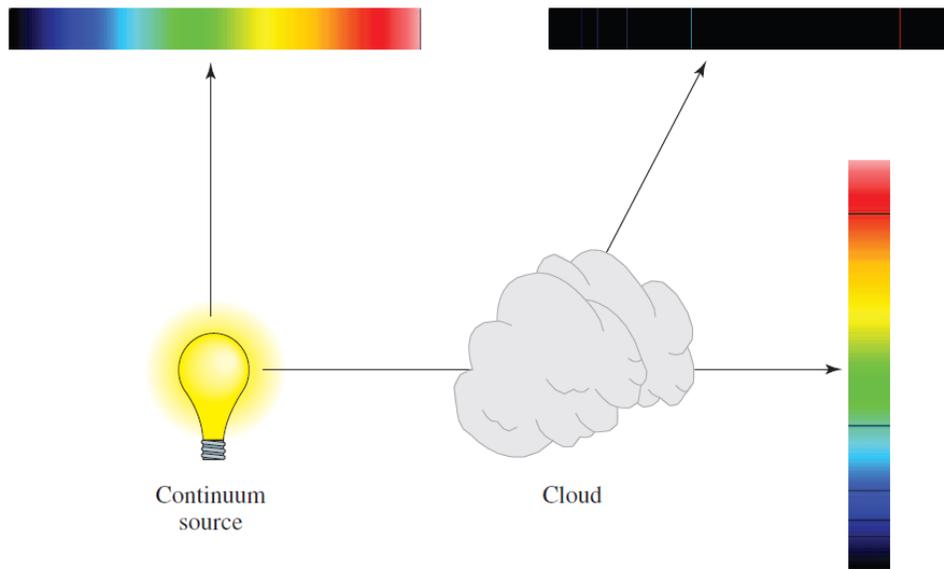
But first, here's a bit of background.

## 1.2 Kirchhoff's Laws

Gustav Kirchhoff first described various types of spectra and their sources in the late 1850s. He stated his conclusions in the form of three laws, which although a bit simplistic, are useful ways to describe different kinds of spectral distributions. A simple diagrammatic representation of Kirchhoff's laws can be seen in Figure 2.



**Figure 1.** The different bands of the electromagnetic spectrum and how well they can pass through Earth's atmosphere. Credits: *Openstax Astronomy*, Fraknoi et. al 2016.



**Figure 2.** Kirchhoff's laws for the production of continuous spectra (1<sup>st</sup> law, upper left), emission spectra (2<sup>nd</sup> law, upper right), and absorption spectra (3<sup>rd</sup> law, lower right). Credits: *Foundations of Astrophysics*, Ryden and Peterson, 2010.

### 1.2.1 Kirchhoff's First Law

Kirchhoff's first law states that solids, liquids, and dense gases give off a **continuous spectrum**. This may be observed by measuring the spectral distribution of an incandescent light bulb, a candle or an LED. We'll revisit the first law more in the blackbody subsection. It's important to remember that this continuous spectrum depends on the source's temperature.

### 1.2.2 Kirchhoff's Second Law

A hot gas produces a spectrum with light emitting at particular wavelengths. What's behind this? Take, for example, a tenuous gas cloud made of Hydrogen-I atoms. The Bohr model of a Hydrogen-I atom shows a proton in the middle of the atom with an electron orbiting around it. We say that there are several orbital states, 1, 2, 3..., with energies  $E_1, E_2, E_3, \dots$  at which the electron can orbit the proton, each with a specific energy associated with it. The  $n = 1$  or **ground state** is the lowest energy state and is the most stable. If the electron happens to be in the  $n$  state (where  $n > 1$ ) and wants to be at the ground  $n = 1$  state instead, it would need to lose  $E_n - E_1 = \Delta E_{n1}$  energy. When the electron makes the jump to the  $n = 1$  state, a photon of with wavelength  $\lambda = \Delta E_{n1}/hc$  (from Equation 1) is emitted so the electron loses that exact amount of energy.

$$E = hf = \frac{hc}{\lambda} \quad (1)$$

In general, any particle with an electron making a jump from a higher to lower energy state  $n = b$  to  $n = a$  will emit a photon with energy  $E_b - E_a = \Delta E_{ba}$ . The idea is that an energised, low-density gas will have lots of particles energised to a higher energy level. When they jump to a lower energy level, quantum mechanics dictates that photons with a very specific energy ( $\Delta E$ ) and thus wavelength will be emitted. Thus, a non-dense heated gas will produce what is called an **emission spectrum**, with light at specific wavelengths emitted from the gas.

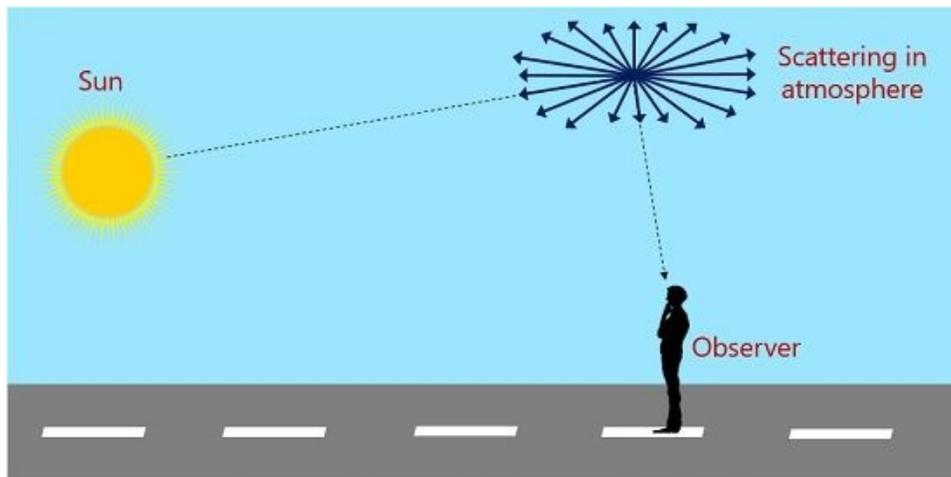
### 1.2.3 Kirchhoff's Third Law

Kirchhoff's third law states that a cool gas in front of a hot, dense object (think Kirchhoff's first law) will result in a spectrum that *appears* to be continuous, but will have some gaps in the continuum at specific wavelengths. Now why would that be? The idea is that the cool, tenuous gas will have several particles at lower energy levels. Similarly to what we have discussed before, if a particle's electron is at a lower energy state  $a$  and wants to exist instead at a higher state  $b$ , it needs to absorb some particular energy  $E_b - E_a = \Delta E$ . The electron can get this energy from photons with  $\Delta E$  energy, which correspond to  $\lambda = hc/E$  wavelength (Equation 1). Since a continuous spectrum has light from every wavelength,

light with wavelength  $\lambda$  gets absorbed as it passes through the gas, leaving the other part of the spectrum unscathed. For a review on atomic structure and how photons of specific wavelengths are emitted and absorbed, please see pages 166–176 from Openstax Astronomy<sup>1</sup>.

### 1.3 The Spectrum of the Blue Sky

Now where does the blue sky's spectrum come from? The gasses in the atmosphere tend to scatter sunlight through a process called **Rayleigh scattering**. Rayleigh scattering is an elastic process, which means that the photons which hit the atmospheric gas molecules and the subsequently scattered photons have the same wavelength. The photons are not absorbed by the molecules, and are scattered in a purely physical process. All this is to say that the energies of scattered photons do not change. Figure 3 shows how we observe light from the blue sky through atmospheric scattering. The formula for the intensity of light through Rayleigh scattering is given by Equation 2.



**Figure 3.** How gases in the atmosphere scatter sunlight through Rayleigh Scattering. Credits: Circuit Globe.

$$I = I_0 \frac{8\pi^4 N \alpha^2}{\lambda^4 R^2} (1 + \cos^2 \theta) \quad (2)$$

Here  $I_0$  is the intensity at the top of the atmosphere,  $N$  is the number of scatterers in the atmosphere,  $\alpha$  is the polarisability,  $\lambda$  is the wavelength of the scattered light,  $R$  is the distance from the particle to the observer, and  $\theta$  is the scattering angle. A lot of variables dictate Rayleigh scattering, but if we make a single observation, we can focus on the effects of the  $\lambda^{-4}$  term, holding all other variables constant. Scattering has a strong wavelength dependence ( $\lambda^{-4}$ ), which means Rayleigh scattering tends to scatter some wavelengths more than others.

## 1.4 The Sun's Spectrum

### 1.4.1 The blackbody spectrum

As Kirchhoff's first law suggests, dense Baryonic matter emits some continuous spectrum. Additionally, dense Baryonic matter must absorb light to some degree as well. How much light of any wavelength can a dense object emit and absorb? That can depend on several properties. A water bottle and the moon will have largely different absorption and emission behaviours. To have some sort of a baseline, we imagine an idealised object called a **blackbody**. The blackbody does not reflect or scatter electromagnetic radiation, but absorbs everything. The blackbody also emits a continuous radiation spectrum which depends on its temperature. The **Stefan-Boltzmann law** (Equation 3) defines that the total rate of energy emitted per unit area of a blackbody is proportional to the fourth power of its absolute temperature.

$$E = \sigma T^4 \quad (3)$$

where  $\sigma = 5.67 \times 10^{-8} \text{Js}^{-1} \text{m}^{-2} \text{K}^{-4}$ . The 'shape' of a blackbody spectrum is defined by the Planck spectrum (Equation 4):

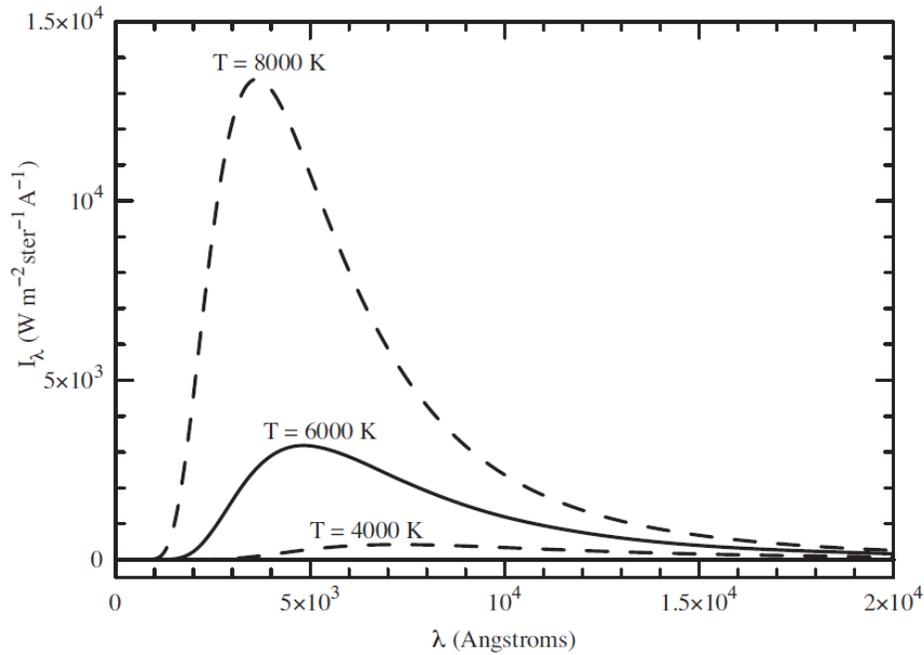
$$I_\lambda = \frac{2hc^2}{\lambda^5} \frac{1}{e^{hc/\lambda kT} - 1} \quad (4)$$

where  $I_\lambda$  is the power density from emission of wavelength  $\lambda$  light.  $h$  is the Planck constant,  $c$  is the speed of light, and  $k$  is the Boltzmann constant. Figure 4 shows what this distribution looks like.

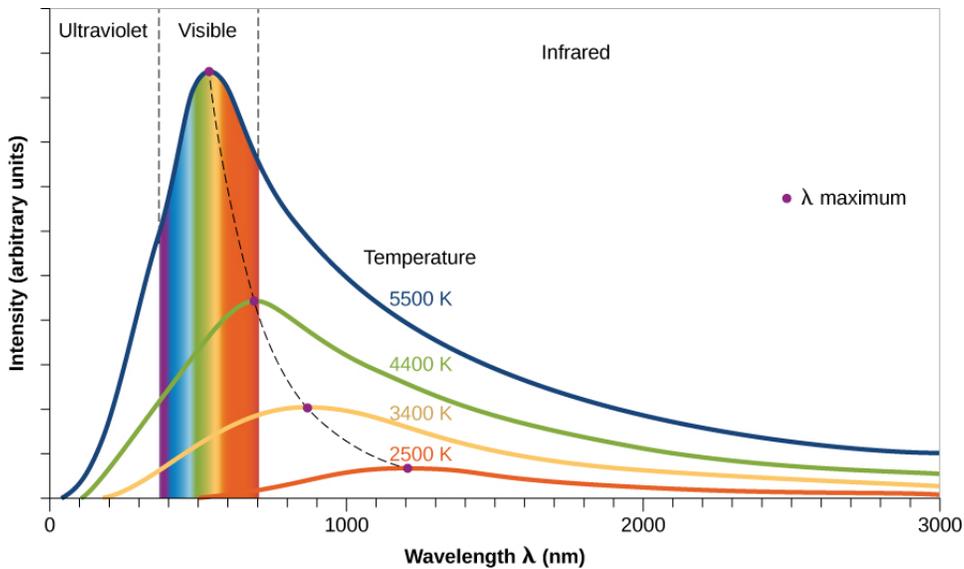
Figure 4 shows that a blackbody emits light at all wavelengths but in different amounts. The wavelength at which the blackbody emits at the highest power density is called the **peak wavelength**. **Wien's law** states that the peak wavelength of a blackbody is inversely proportional to its temperature (Equation 5). For low temperatures,  $\lambda_{max}$  is large and thus the peak emission is redder. Conversely, higher temperatures mean a shorter peak wavelength and a predominantly bluer emission. Figure 5 highlights this shift. This is also why as you heat up a piece of metal, it begins by glowing a dull red, and changes to a 'white hot' as you continue to heat it. If you keep on heating the metal, it will eventually appear blue.

$$\lambda_{max} \approx \frac{3 \times 10^6}{T}. \quad (5)$$

We're really interested in the blackbody spectrum because stellar spectra (including the Sun's) are



**Figure 4.** The Planck function, with power density per wavelength on the y-axis and wavelength on the x-axis, displays a continuous spectrum. Functions for temperatures 8000 K, 6000 K, and 4000 K are shown from top to bottom. See how the shape and position of the peak change with temperature. Credits: *Foundations of Astrophysics*, Ryden and Peterson, 2010.



**Figure 5.** Graph of blackbody spectra at different temperatures, showing how peak wavelength changes with respect to temperature according to Wein's Law. The visible light spectrum has been coloured in for reference. Credits: *Openstax Astronomy*, Fraknoi et. al 2016.

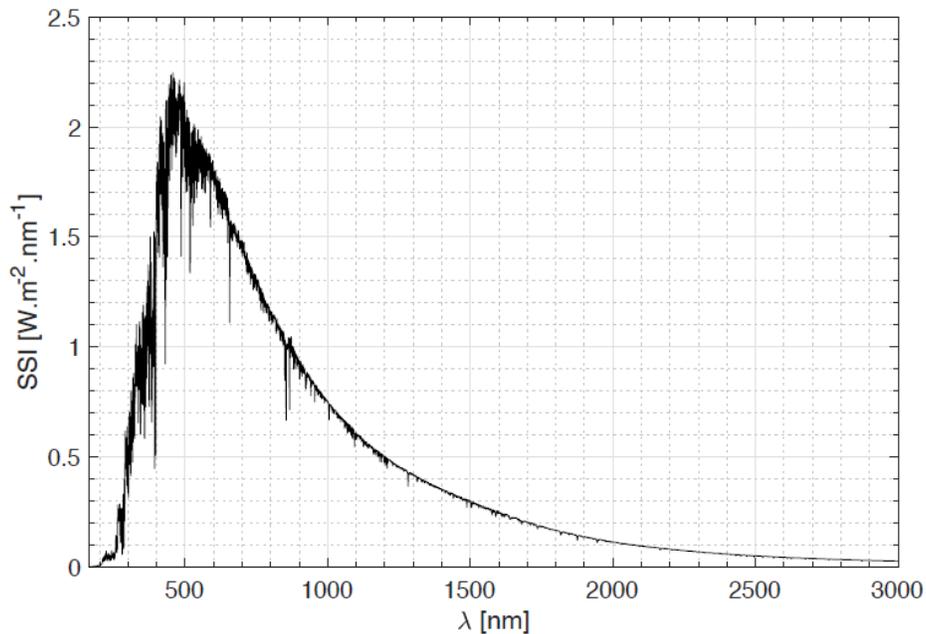
extremely well modelled by a blackbody with an absolute temperature equal to the temperature of the star's photosphere. In fact it is possible to find the surface temperature for a star by comparing its spectrum to an equivalent blackbody according to Wein's law. If we imagine a star of radius  $R$  as a spherical

blackbody, we can find the luminosity (total power emitted) of a star from Equation 3 to be:

$$L = 4\pi R^2 \sigma T^4 \quad (6)$$

### 1.4.2 Fraunhofer Lines

So what does a star's spectrum look like? Figure 6 shows the spectrum of our sun taken by an ESA solar instrument onboard the ISS in 2008. You'll notice several similarities and differences between the solar and blackbody spectrum. The shape is very comparable, but Figure 6 is quite a bit more...spiky than a curve from Figure 4. Why is this so?

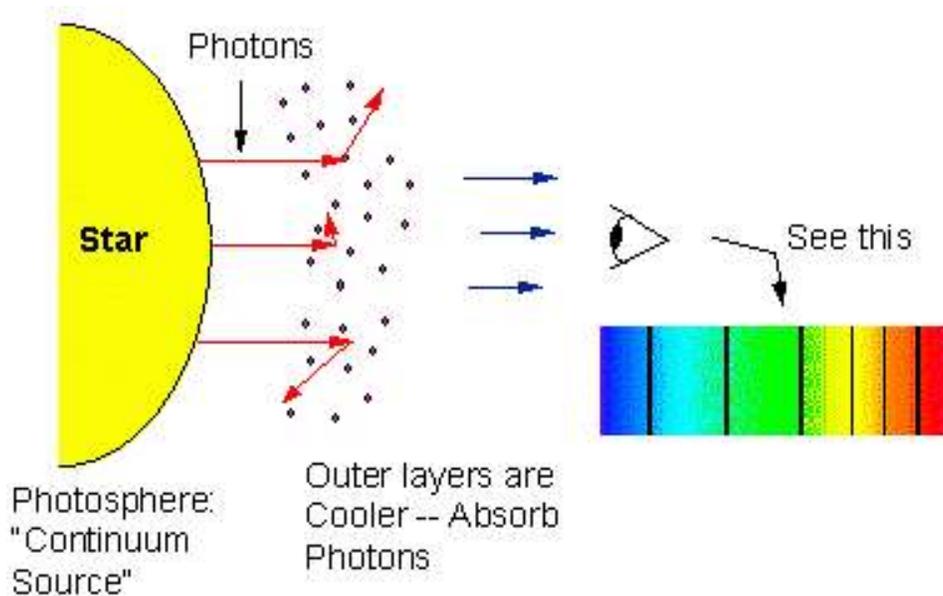


**Figure 6.** Graph showing the spectrum of Sol. Credits: *ESA*.

Scientists in the olden days did not view the solar spectrum in the convenient power-density vs. wavelength format like in Figure 6. Newton began by dispersing sunlight through a prism, and observed a spectrum in the shape of a continuous rainbow of colours. By 1802, William Wollaston's improved spectrometer, which focused the Sun's spectrum on a screen, could observe previously unnoticed features. Wollaston saw some gaps in between the ranges of colour, appearing as dark bands in the solar spectrum. These gaps were thought to be natural 'boundaries' in between colours at the time. In 1815, however, the German physicist Joseph Fraunhofer found about 600 dark lines in the continuous solar spectrum, putting an end to the natural boundary hypothesis.

Of course, the reason for these peculiar dips in the continuous solar spectrum is a great demonstration of

Kirchhoff's third law. The chromosphere (the layer of atmosphere of the sun above the photosphere) is extremely tenuous and acts as a cool, non-dense gas which absorbs some wavelengths from the continuous spectrum emitted by the photosphere. See Figure 7.



**Figure 7.** How the solar chromosphere acts as a cool, tenuous gas in front of the continuous solar spectrum, demonstrating Kirchhoff's third law. Credits: Professor Terry Herter, *Cornell University*.

This is exciting news! Harkening back to the atomic reasons behind emission and absorption, we know that an absorption line corresponds to photons with energy  $\Delta E = hc/\lambda$ . This energy  $\Delta E$  signifies the energy difference in electron states between which our gas particle's electron has jumped. It is very unique to the particular electron state numbers and element/compound. Thus, by knowing the absorbed wavelength, we can make a pretty good guess as to what element or compound is present in the gas. Indeed, in the 1860s English astronomers Sir William Huggins and Lady Margaret Huggins succeeded in identifying Fraunhofer lines to be absorptions by known elements on Earth. Today, spectroscopic analysis remains to be one of the cornerstones of astronomical research.

## 2 Apparatus

### 2.1 The Spectrometer

You'll be using the BLUE-Wave VIS-50 miniature bench spectrometer from StellerNet. This little spectrometer can show spectra in the 350–1150 nm range with a spectral; resolution of 1.6 nm. **Please take care while handling the spectrometer, as it is a very costly piece of equipment.** The spectroscope comes with a USB cable to connect it with a computer with the SpectraWiz software installed. Additionally, the spectrometer comes with a fibre-optic cable to make it easier to collect relevant light samples. **Minimise**

**bending the cable!** It can get damaged easily so do handle it with care.



**Figure 8.** The StellerNet BLUE-Wave VIS50.

## 2.2 DNSI Device

There are a couple of ways to extract the sun's spectrum. Direct Normal Solar Irradiation (DNSI) is one, and it entails limiting a fibre's FOV to  $5^\circ$  around the Sun before measuring the spectrum. It is an easy, affordable way to get a measure of the Sun's spectrum. In our case, we use PVC pipe with a Teflon fibre feed towards one end. The device comes with a tripod which you can use to hold it steady and adjust the direction so the open end of the tube is directly facing the sun. It is crucial that we **never look at the sun!** To help us steer the tube into the right position without looking anywhere near the Sun, it comes with two sights perpendicular to each other. These sights will cast a shadow behind them, which you will align to properly aim the tube.

## 2.3 Miscellaneous

Additionally, grab some aluminium foil, a ruler/scissors to cut the foil, and a pin (any pin will do).

## 3 Procedure

For this experiment, you'll need the spectrometer, fibre-optic cable, the spectrometer's USB AB cable, the DNSI device, tripod, aluminium foil, ruler/scissors, a pin, and a laptop with StellarNet's SpectraWiz software installed. If you don't have the VIS-50 drivers installed or don't have SpectraWiz on your PC, you can download the software from the lab's [AstroLAB page](#). There's also a little video tutorial to guide you through it.

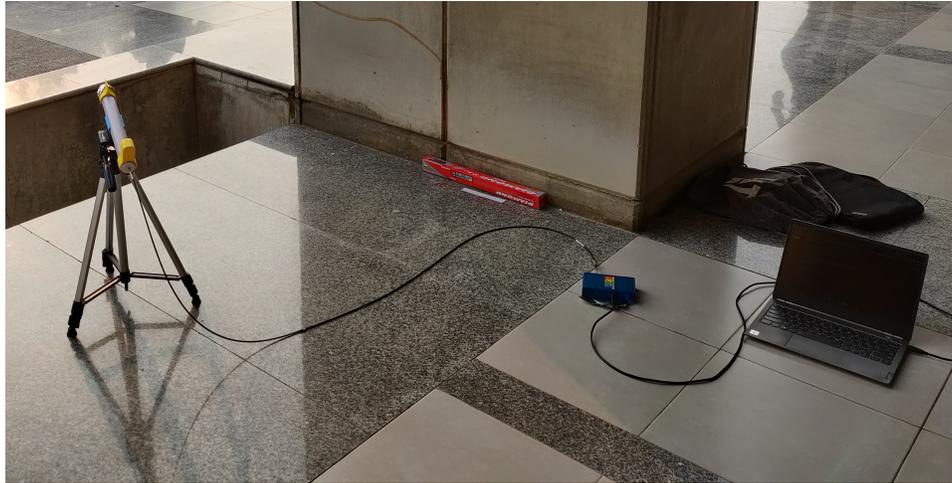


**Figure 9.** The DNSI device and tripod.



**Figure 10.** Don't forget to get some foil and a pin along with something to cut the foil.

This experiment requires you taking your setup outside, so make sure to move the items carefully to your location! Getting someone to help you move might be good. Using a weather forecast, ensure that you're going out on a clear day with some blue sky visible. Rain could easily damage the equipment, so let's stay clear of that. One of the outdoor classrooms might be preferable locations, as you will have power access for your laptops and some shade for you to sit in. You should also feel free to use the outdoor classroom furniture. If battery isn't an issue, another good location is right outside the entrance of the SSE.



**Figure 11.** What your setup might look like.

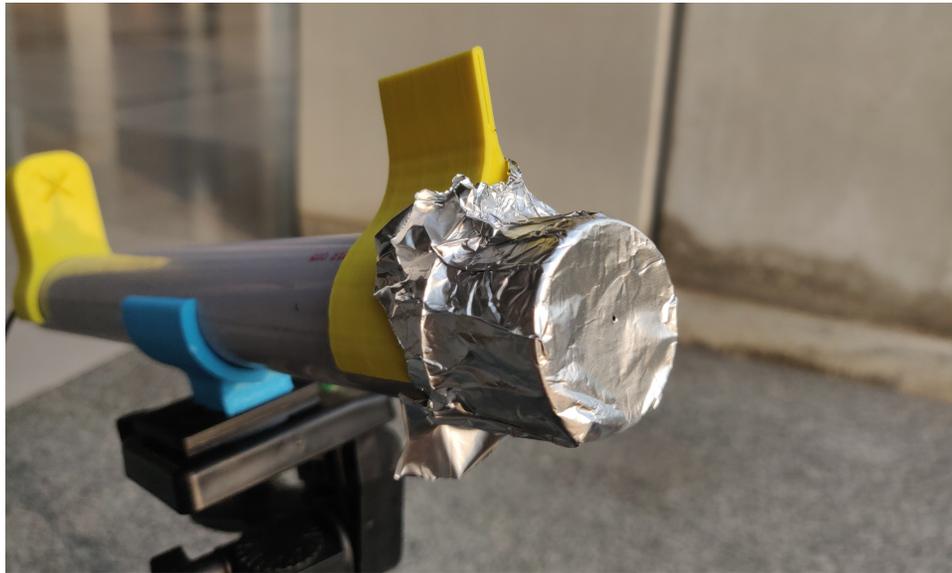
Spread out the tripod and attach the DNSI tube on top of it before placing the tripod on a flat surface. Insert one end of the fibre-optic cable (the end without the washer) into the tube's back end. **While keeping the tube away from the sun**, aim the DNSI's open end towards a patch of blue sky. Try to keep it away from any clouds.

Attach the other end of the fibre-optic cable to the spectrometer and turn the washer to secure it. Place your laptop at a suitable location and plug in the spectrometer to the laptop via the USB cable. If the SpectraWiz software and drivers have been installed correctly, the green LED on the spectroscope should light up.

Open SpectraWiz. You should now be able to see some peaks being displayed. If the signal seems to be small and doesn't fill up most of the graph, increase the spectrometer integration time by selecting 'Setup' from the top toolbar and clicking on 'Detector integration time' from the drop-down menu. You can set the integration anywhere from 1–65535 ms. Conversely, if the signal seems to be saturated (so large that it touches the top of the graph), decrease the spectrometer integration time. Once you're satisfied that the signal is covering the maximum area in the graph without saturating, you're good! You might want to collect several scans and average them for better accuracy. Select 'Setup' from the top toolbar and click on 'Number of scans to average' (10–15 should be more than enough). Once it looks like the signal isn't changing much, you can click the save icon to save the spectrum to disk in an '.SSM' file. Take a couple of more exposures. We now have some blue sky spectra to work with!

Next, we'll want to measure the spectrum of our host star. Before that, however, we will need to somehow decrease the sunlight reaching the fibre. Sunlight is so bright that even with an integration time of 1 ms, the signal can get saturated. One simple way to accomplish this is to cover the open end of the DNSI tube with aluminium foil and making a small hole about near the centre. So take out your aluminium foil cut out a roughly 7 cm × 7 cm piece. Cover the open end of the DNSI tube with the foil and try to make it as

flat and taut as possible. Then, carefully make one pinprick on the foil's surface.



**Figure 12.** Cover the open end of the tube with foil and make a pinhole.

We will now try to properly align the DNSI tube to be perpendicular to the sun. To reiterate, **Do NOT look at or near the sun** in order to align the DNSI tube. The front sight on the DNSI tube will cast a shadow on the back sight, which has a cross centred on it, which will help make sure that the tube is well aligned. This will also make sure that you'll be facing *away* from the sun while you align.

Once you're satisfied, focus your attention towards SpectraWiz. At this point, it is an exercise in trial and error to make sure you're able to get just enough light on the fibre to obtain a reasonable spectrum. Too much and it can saturate the CCD, too little and the spectrum might not be accurate. We'd recommend keeping the integration time to 1 ms and the number of scans to average 3–5. Make small adjustments and see where you might get a reasonable spectrum. You may need to make another pinprick if you can't get a bright enough spectrum, or discard the piece of foil and use a new one in case the spectrum remains saturated. Once you've gotten 1–2 good spectra, you're done with data collection!

## 4 Identifying Spectra

Now that we've collected our data, we can begin identifying the absorption lines within the blue sky spectrum and the solar spectrum! Additionally, it'll be fun to identify the same emission lines on a 'pure' solar spectrum. The American Society for Testing and Materials (ASTM) developed an air mass zero (outside the atmosphere) reference solar spectrum called ASTM E-490. ASTM E-490 solar spectral irradiance is based on data from satellites, space shuttle missions, high-altitude aircraft, rocket soundings, ground-based solar telescopes, and modelled spectral irradiance. It's pretty accurate! We've included an ASTM E-490 spectrum within the relevant range at the end of this manual, which you may use to identify

these lines. Alternatively, the ASTM E-490 AM0 data is available in a CSV file on the lab's [AstroLAB page](#), which you can use to create your own plot.

We should now plot our sky and solar spectra onto the same plot for identification and analysis. It will make identification easier if you normalise both spectra such that both peak wavelengths occur at a count density of 1. You may plot them however you wish, although the lab [web-page](#) has the [Plotting Spectra with Python and MATLAB](#) video tutorial along with the relevant plotting code.

**[Q]** Identify (digitally or with a writing instrument) the absorption lines in Table 1 on your copy of the blue sky spectrum and solar spectrum, as well as on the ASTM E-490 spectrum. If your spectra don't seem to show a particular line, do your best to identify where you should see it. Print and attach copies of the identified lines along with your lab notes.

**[Q]** Some elements, for example  $O_2$  and  $Fe$ , have multiple absorption lines. Why is that?

**[Q]** Were you able to differentiate the  $D_1$  and  $D_2$  absorption lines in your spectra? If not, why not?

**[Q]** Did you find all absorption lines in your blue sky spectrum, solar spectrum, and the ASTM E-490? If not, why not? What can you say about the differences in the compositions of Earth's atmosphere and the solar chromosphere?

**[Q]** Compare your blue sky spectrum and your solar spectrum closely. Can you figure out why the sky is blue?

Designation	Element	Wavelength (nm)
C	$H\alpha$	656.281
b	Mg/Fe	516.7–518.4
e	Fe	437.355
F	$H\beta$	486.761
G	Fe/Ca	430.7
$E_2$	Fe	527.039
$D_1$	Na	589.592
$D_2$	Na	588.995
A	$O_2$	759.370
a	$O_2$	627.661
B	$O_2$	686.719
K	$Ca^+$	393.366
H	$Ca^+$	396.847
c	Fe	495.761
-	$H_2O$	720–740

**Table 1.** Some common Fraunhofer plus water absorption lines.

## Acknowledgements

This lab was created with media from a wide range of sources. In particular, the textbooks *OpenStax Astronomy* (Andrew Fraknoi, David Morrison, Sidney C. Wolff et. al.) and *Foundations of Astrophysics* (Barbara Ryden and Bradley Peterson) provided diagrams and are referred to for further reading. Images from the European Space Agency, Professor Terry Herter's (Cornell University) Astronomy 101 course, and *Near IR Imaging of Galaxies Under Light Pollution* by Satoru Takagi were also used. In addition, *The Mathematics of Rayleigh Scattering* by Alan Zucconi and *Water Absorption Spectrum* by Professor Matrin Chaplin (London South Bank University) were extremely informative. This document was built upon the [Scientific Reports](#) Overleaf Template, which is licensed under LPPL Version 1.3c.

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