Atomic Spectroscopy for Astronomy[1]

Video: Light: Crash Course Astronomy #24 (https://youtu.be/jjy-eqWM38g)
https://webbtelescope.org/contents/media/videos/2018/37/1181-Video

INTRODUCTION

One of the most amazing properties of atoms and molecules is that they will only emit or absorb specific wavelengths of light. In 1814, Joseph Fraunhofer observed that sunlight can be dispersed into its component colors by passing it through a prism, beginning the field of spectroscopy. In 1861, Robert Bunsen and Gustav Kirchhoff discovered that laboratory flames from natural gas burners (now known as Bunsen burners) produced characteristic bright lines from various metal salts. Some of the lines had the same wavelengths as Fraunhofer's lines. Eventually, chemists came to know that each element, as a gas phase atom, has its own characteristic line spectrum, or "fingerprint." These "fingerprints" allowed chemists to identify the component atoms in unknown mixtures.

Spectroscopy

Spectroscopy allows us to identify gases in planetary atmospheres and minerals on planetary surfaces; figure out what stars are made of and how fast they are rotating; detect and characterize planets orbiting distant stars; measure the temperature and speed of gases in the center of an active galaxy; infer the presence of black holes and dark matter; unravel interactions between colliding galaxies; and help calculate the expansion rate and age of the universe.[2]

Sunlight contains all the visible colors (red, orange, yellow, green, blue, indigo, and violet; ROYGBIV). So, when sunlight goes through a prism the light exiting the prism is separated into the individual colors.

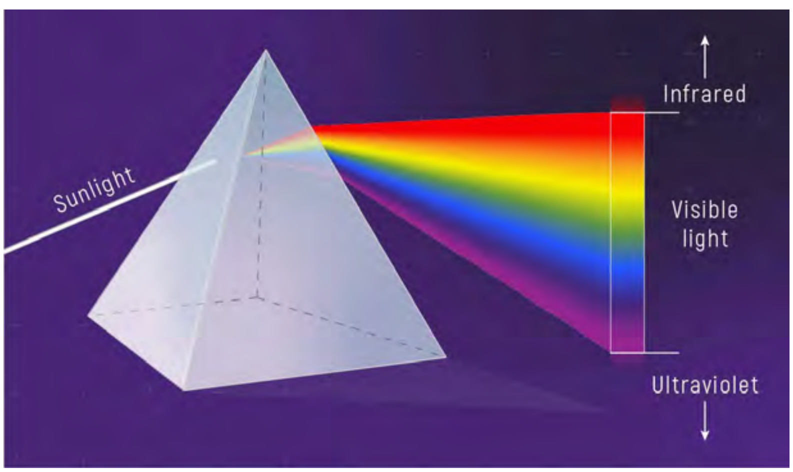

Figure 1. Sunlight that passes through a prism naturally separates into its component colors in a very specific order—rainbow order—based on wavelength. This rainbow is known as the visible spectrum. In addition to visible light, sunlight also contains significant amounts of infrared and ultraviolet light, both of which are invisible to human eyes. Credit: NASA, ESA, L. Hustak (STScI).

Hot or energetic gases also give off light such as neon lights. Unlike sunlight, the light emitted from hot gases is not continuous. These gases emit only specific wavelengths of light like in Figure 2.

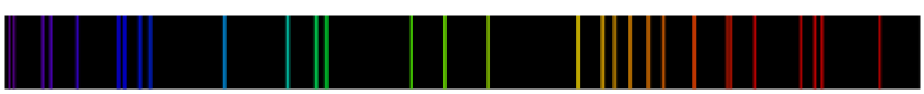

Figure 2. Line Emission spectrum from a hot gas sample.

[1] **Adapted from:** P.E. Siska, *Honors General chemistry laboratory manual,* University of Pittsburgh.

[2] https://webbtelescope.org/contents/articles/spectroscopy-101--introduction.html (Accessed 5/30/2023).

The lines observed in the spectra are some of the strongest evidences that atoms and molecules have **quantized** (can only have specific numeric values) energy levels. Line emission spectra results from "transitions" of an atom's electrons from higher to lower energy levels (orbitals). The energy lost by the atom appears as a newly created photon of light. The difference in the atom's energy level transitions (Figure 3) are equal to the energy of the emitted light (Equation 1).

$$\Delta E_{atom} = E_{level2} - E_{level1} = E_{light} \quad \textbf{(1)}$$

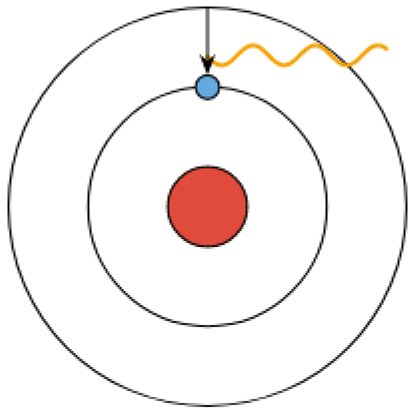

Figure 3. The electron (blue circle) transitions from high to low energy levels (black lines) and emits light of the same energy. Red circle is the atom's nucleus.

Light is radiant energy whose **wavelength (λ)** is the distance traveled to complete one full wave cycle. The **frequency** (v) of light refers to the number of cycles passing a point in one second. Low-energy light has a long wavelength and a low frequency. High-energy light has a short wavelength and a high frequency. Each of these wave properties is shown in Figure 4. Light is a form of energy that travels with wavelike motion at a velocity of 300,000,000 meters per second. Mathematically,

$$E_{light} = h\nu = hc/\lambda \quad \textbf{(2)}$$

$$\nu = c/\lambda \quad \textbf{(3)}$$

where E is the energy in Joules, h is Planck's constant (6.63×10^{-34} J•s), c is the speed of light (2.9979×10^{8} m/s), v (nu) is the frequency in Hertz (s^{-1}), and λ (lambda) is the wavelength in meters (m).

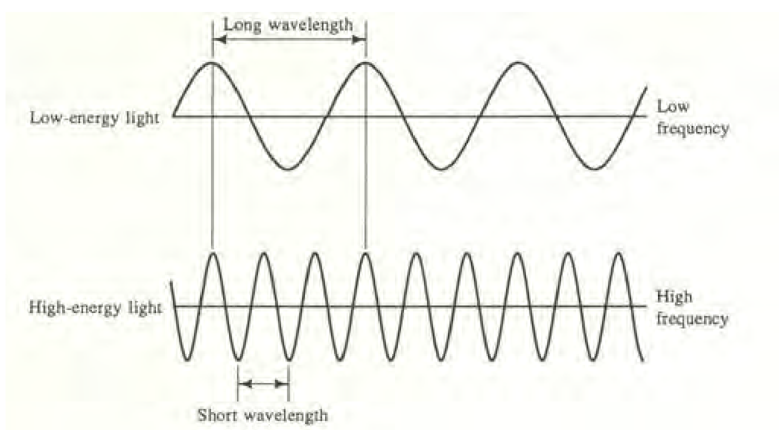

Figure 4. Characteristics of electromagnetic radiation or light.

Every element has its own unique electronic energy levels (like a fingerprint); therefore, every element has its own unique emission spectra (Figure 5). Note that these spectra are mostly dark except for the light emitted by the hot gas atoms.

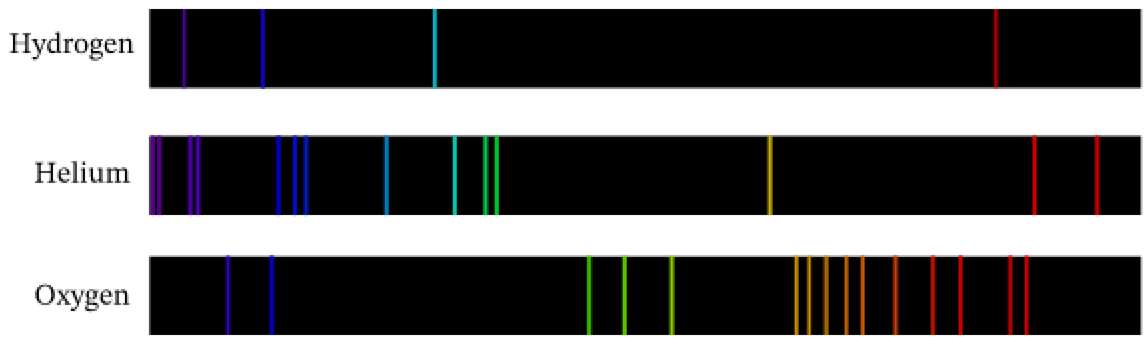

Figure 5. Unique emission line spectra for hydrogen, helium, and oxygen atoms.

Comparing emission spectra of known elements can be used to identify unknown gases on other planets and celestial bodies using a telescope and <u>spectroscope</u>. A spectroscope (Figure 6) is an instrument that disperses light passed through a small slit using a grating into a spectrum, like a prism. The dispersed light lands on a detector to reveal the emission spectrum.

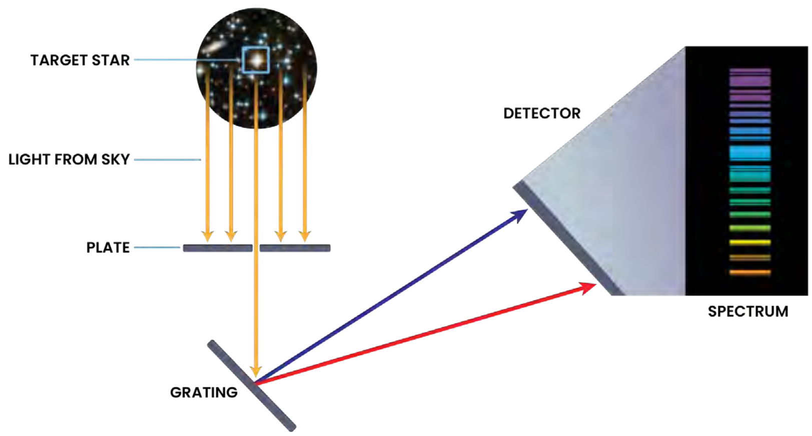

Figure 6. Schematic of a spectroscope. https://hubblesite.org/contents/articles/spectroscopy-reading-the-rainbow#:~:text=A%20spectrograph%20%E2%80%94%20sometimes%20called%20a,the%20material%20interacting%20with%20it.

<u>PROCEDURE:</u>

In this experiment, a hand-held spectroscope is used to observe and identify the atoms in a gas tube and to record the wavelengths of light emitted by a hydrogen atom gas tube. The spectroscope, figure 7, gives spectral lines which can be viewed against a wavelength scale to an accuracy of ±20 nm, (1 nm = 10^{-9}m). If you can't see an image on the scale like the one in Figure 2, you may need to adjust the light entering the slit or where your eye is looking. The scale represents wavelengths from 400 nm to 700 nm. The digit 4 is read as 400 nm, 5 as 500 nm and 6 as 600 nm. There are ten divisions between each number on the scale; therefore, each division is 10 nm. For example, the scale divisions between 4 and 5 are read as: 410, 420, 430, 440, 450, 460, 470, 480, and 490 nm. (1 nm = 10^{-9}m).

Similarly, we can attach a spectroscope to a telescope and direct the light on a grating to produce a spectrum and identify atoms on stars.

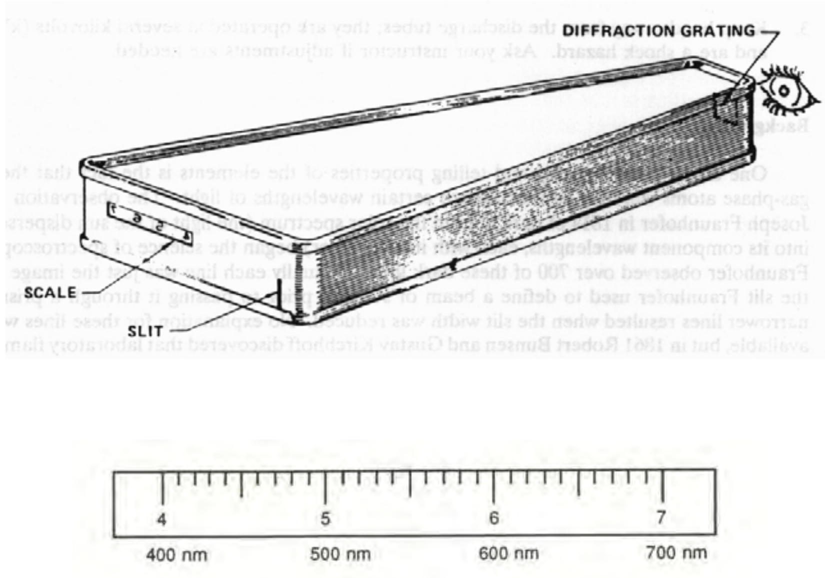

Figure 7. Handheld Spectroscope and Wavelength Scale

You will work in pairs, as this eases the task of recording the wavelengths. However, everyone should observe each tube to get a feel for the differences in the spectra and the difficulties in obtaining accurate data.

For hydrogen atom, observe and record the color of the discharge tube. To observe the spectrum, sit on a stool with your spectroscope quite close (~30 cm away) to the bright capillary in the center of the tube. Read off the wavelengths and colors of each line to your partner, and then let them do the same. On your data sheet, record the observed wavelengths and colors for each line. When you have data for the four visible lines, perform the calculations in the data table to determine the energy (J) corresponding to each line.

Part 1: Compare the spectrum of the discharge tube using the handheld spectroscope and the emission spectrum key to identify the gas in each discharge tube.

Tube Number	Atomic Gas
1	
2	
3	
4	
5	
6	
7	

Part 2: Calculations for Hydrogen Atom Gas

<table>
<tr><th>Gas</th><th>Observed Color of Tube</th><th>Number of Bright lines in Spectrum</th><th>Wavelengths, nm (Color)</th><th>Wavelengths, m</th><th>Frequency (Hz)</th><th>Energy (J)</th></tr>
<tr><td rowspan="5">Hydrogen</td><td rowspan="5"></td><td rowspan="5">4
(410 nm Violet is faint)</td><td>410 (Violet)</td><td></td><td></td><td></td></tr>
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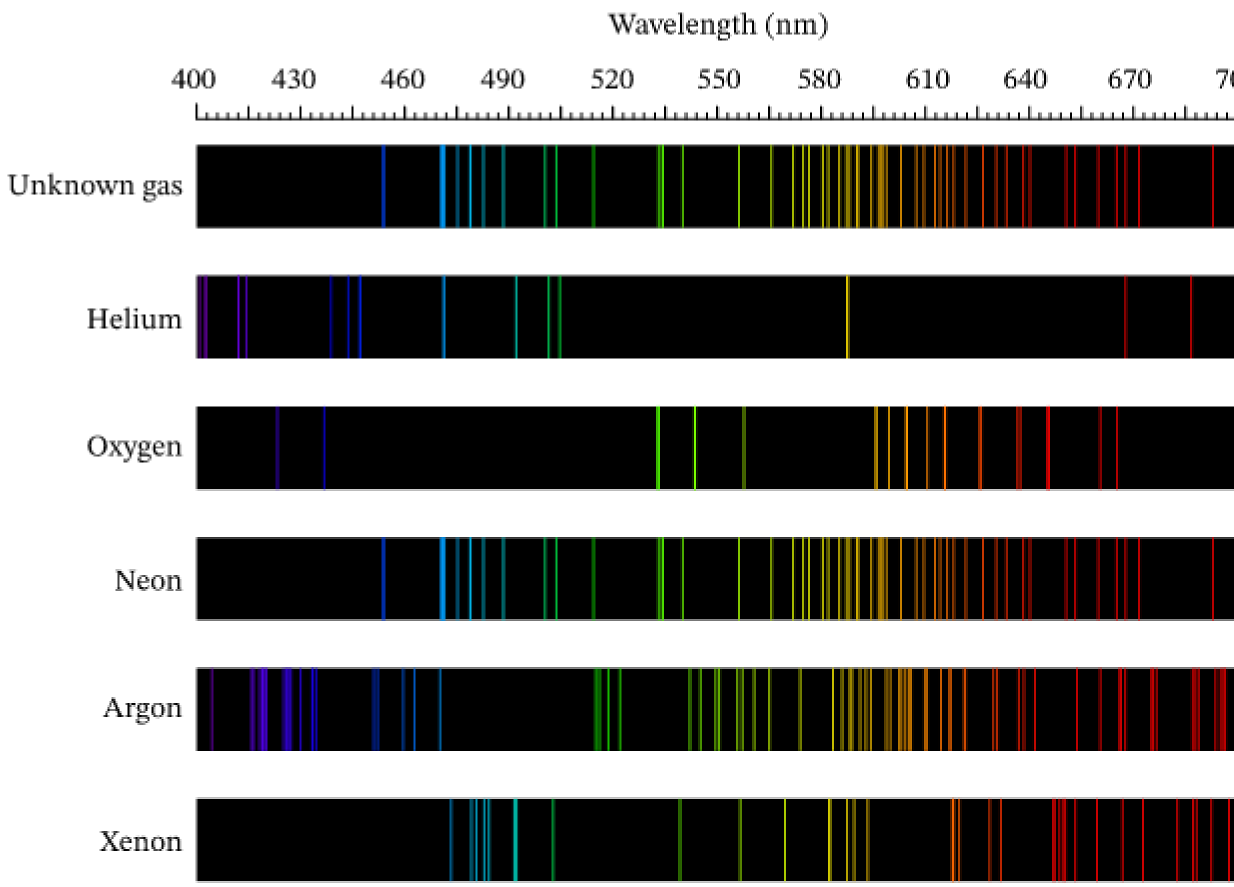
Use the space below and equations 2 and 3 to calculate: a) wavelength (m), b) frequency (Hz) and c) energy (J).

QUESTIONS Name:_______________________________

1. A scientist has a sample of an unknown gas. To identify the gas, he looks at the spectrum of visible light emitted from it when it is heated. This is shown in the figure. Also shown in the figure are the emission spectra of five pure, gaseous elements. Which of the five elements is the unknown gas? https://www.nagwa.com/en/explainers/469167813067/



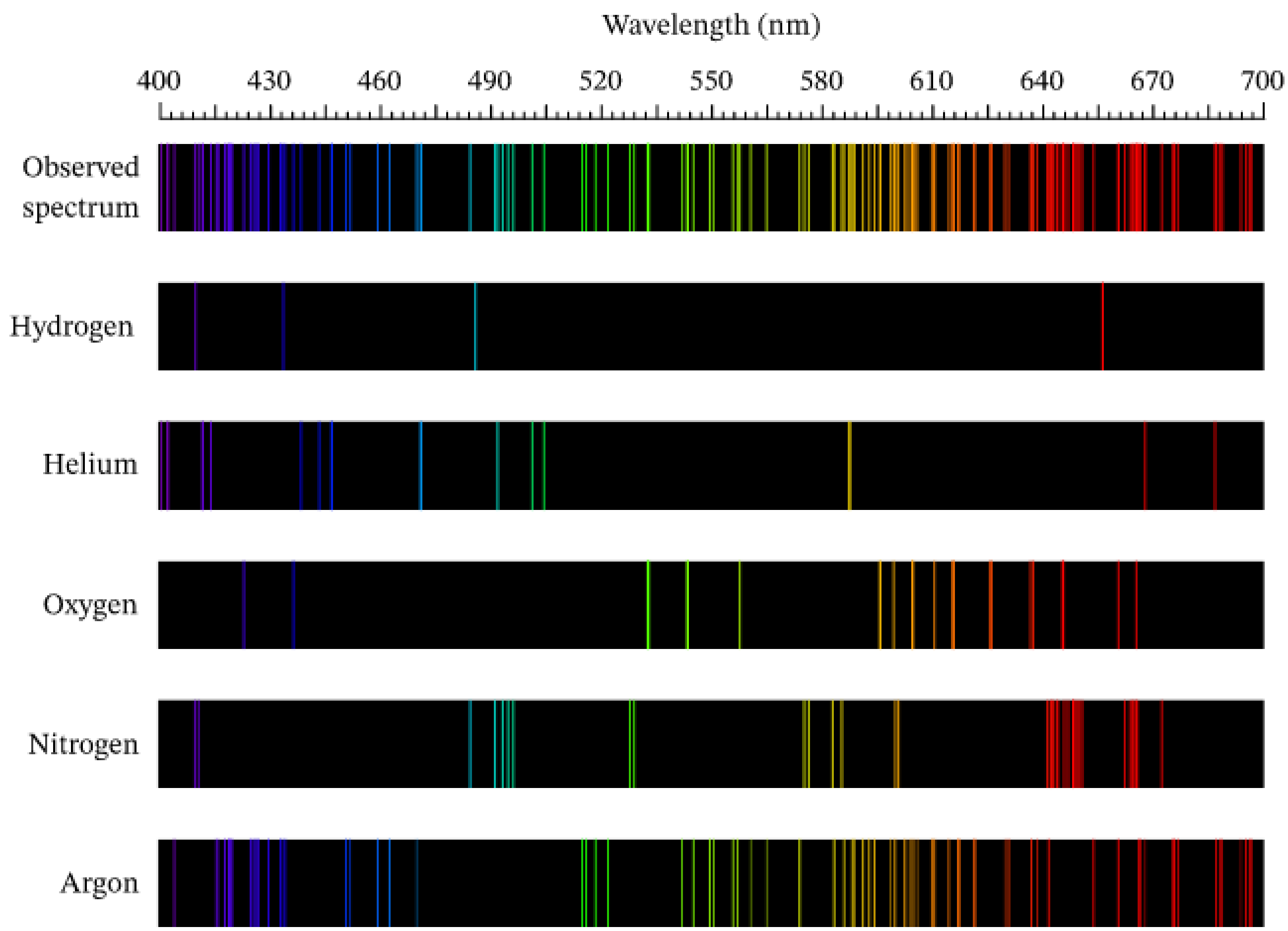
A. Xenon
B. Argon
C. Oxygen
D. Helium
E. Neon

Answer

Let's start by looking where there are definitely no emission lines in the other gases. This unknown gas has no emission lines at around 440 nm or below, so it cannot be helium, oxygen, or argon.

Xenon appears to have some lines that match up, but comparing the lines to neon shows that they match up completely. The unknown gas is thus neon, which is choice E.

2. A scientist has a gas canister that contains a mixture of unknown gases. To identify which gases are in the mixture, she looks at the spectrum of visible light emitted from it when it is heated. This is shown in the figure. Also shown in the figure are the emission spectra of several pure, gaseous elements. Which of the five elements does the mixture contain?



A. Hydrogen, helium, and nitrogen
B. Hydrogen and argon
C. Helium, hydrogen, oxygen, nitrogen, and argon
D. Oxygen, helium, and hydrogen
E. Helium, oxygen, nitrogen, and argon

Answer

This gas mixture has a lot of emission lines, but we just need to find one difference to rule out a particular gas as being part of it. We cannot start by observing where the unknown gas mixture has no emission lines, as it pretty much covers the entire spectrum. So, let's compare each gas one by one.

Hydrogen's lines in the region of purple light seem to match up, but the lines around 485 nm and 655 nm just barely do not. This gas likely does not contain hydrogen.

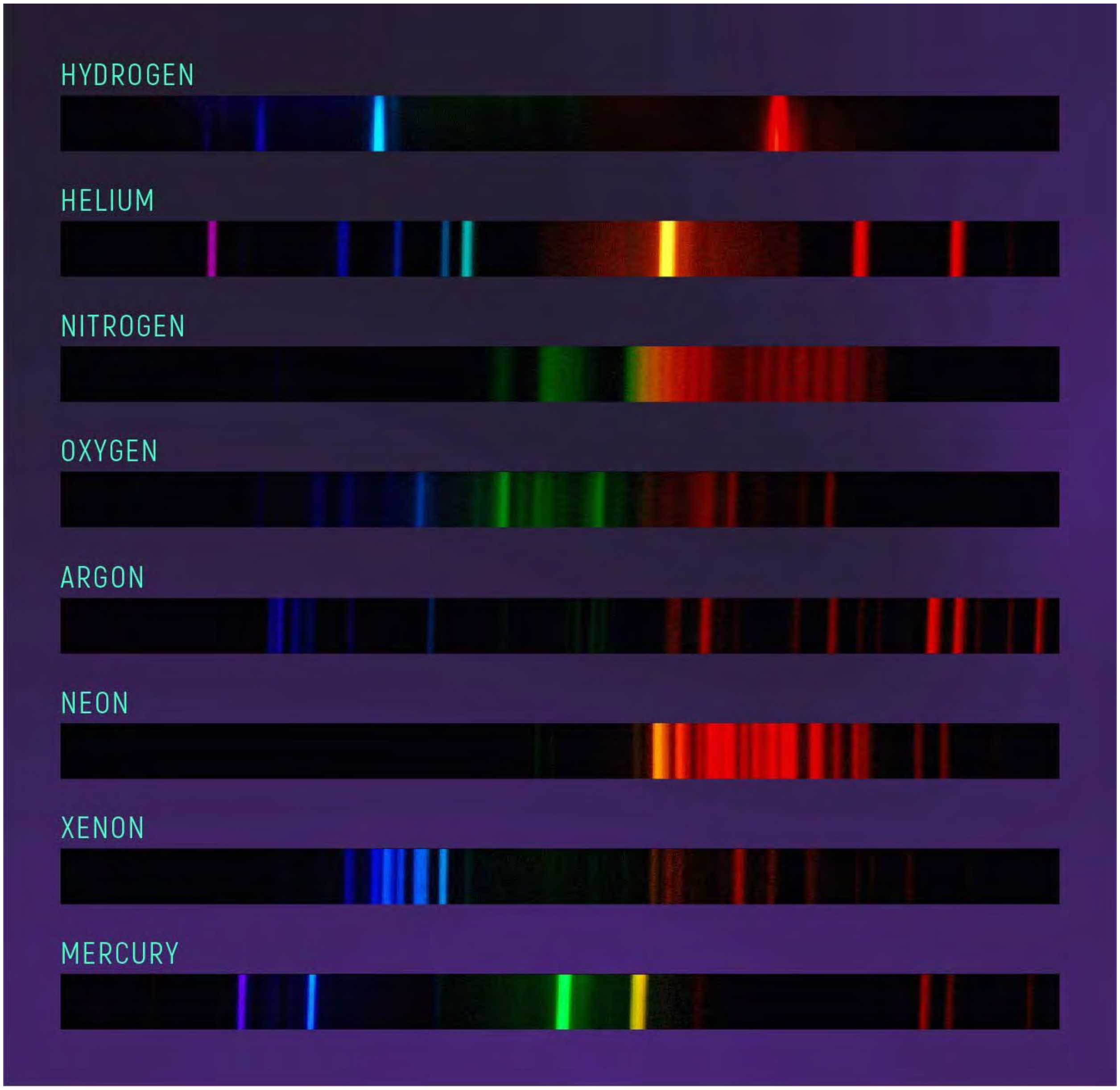
For helium, we see that some of the green lines around 500 nm match up exactly and are not present in any other gas, so it contains helium.

All of oxygen's lines appear to be present within the gas mixture, so it contains oxygen.

The gas mixture's thicker emission lines in the region of red light, around 650 nm, match up with the thick lines of nitrogen in the same region. The gas contains nitrogen.

Finally, we have argon, which fills in the last bits of lines around the regions of purple, yellow, and red light. Most of the emission spectrum appears to be coming from this, so the gas contains argon.

The answer is every gas except for hydrogen. This means the correct answer is choice E, helium, oxygen, nitrogen, and argon.



Key. *Photograph of the emission spectra of gases measured in a laboratory. In the 1850s, scientists discovered that different elements emit different patterns of light when heated in a flame. They noticed that the patterns of known elements studied in the lab correspond to patterns seen in the absorption lines in the Sun.* Credit: M. Richmond, RIT. https://webbtelescope.org/contents/articles/spectroscopy-101--types-of-spectra-and-spectroscopy (5/30/2023).