How can we know what chemical elements are there in stars without going there?

Regarding celestial bodies (such as stars and planets), the French philosopher Auguste Comte wrote in *Cours de philsophie positive* in 1835:

“We understand the possibility of determining their shapes, their distances, their sizes, and motions, whereas never, by any means, will we be able to study their chemical composition, their mineralogic structure, and not at all the nature of organic beings living on their surface.”

However, he was wrong. We now know the chemical compositions of stars. How do we know them?

In an earlier article “Rydberg formula,” we mentioned that an atom emits light with certain wavelengths in suitable conditions. By measuring such wavelengths from stars, we can determine what kind of atoms the stars have.

Let me give you some histories behind it in this article. Earlier we mentioned that Newton used prisms to separate white light (actually the sunlight) into different colors. In 1802, the English chemist William Hyde Wollaston improved on Newton’s method, by using prism more carefully, to separate the sunlight better. Strangely, he found out that there are dark lines in the spectrum. See Fig. 1 for some examples of such a spectrum. Wollaston thought that the dark lines represent the natural boundaries between colors.

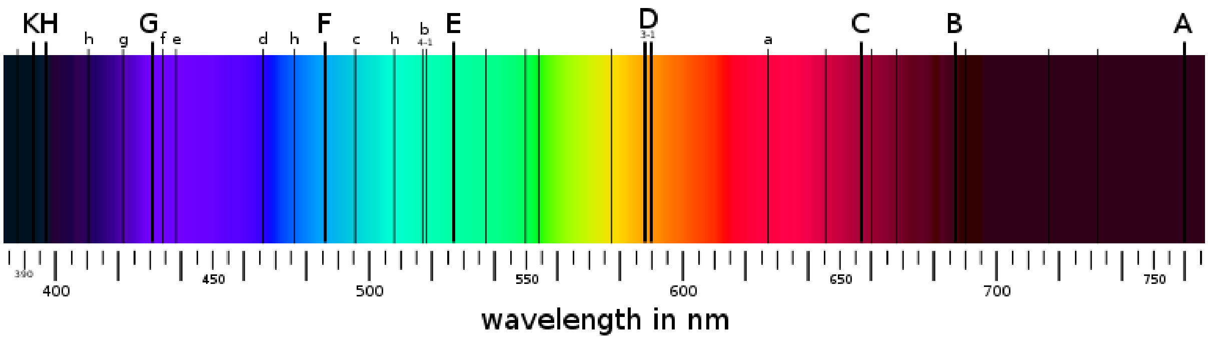

Fig. 1: Fraunhofer lines

A breakthrough was made by the German physicist Joseph Ritter von Fraunhofer in 1815. He developed and used what is called “diffraction grating.” The principle behind it is based on the wave nature of light, which Thomas Young discovered through Young’s interference experiment in 1803. We will explain diffraction in detail in “Diffraction.” Diffraction grating was much better than a prism, not only because it could show the black lines more clearly, but also because it allowed him to determine the actual values for the wavelengths of light. The dark lines are now called “Fraunhofer lines.” See Fig. 1 again. The figure is actually one of the Fraunhofer lines. You also see that they are labeled by alphabets. So, why does the spectrum of the sunlight have these dark lines?

Notice that the lines we talked about in "Rydberg formula" are necessarily bright lines. Atoms emit light with only certain wavelengths. They don't emit other light. Therefore, the light they emit corresponds to bright lines, and the other region in the spectrum is dark because no light with the wavelength of that wide region is emitted.

On the other hand, the dark lines in the solar spectrum (i.e., the spectrum of the sunlight) mean that the sun emits light with every wavelength except for the light that corresponds to the dark lines. The situation is the very opposite. This is strange.

Actually, Fraunhofer himself discovered the first hint to solve this puzzle. He noticed that the wavelengths of some of the dark lines (actually the double D lines in Fig. 1.) coincide with the wavelengths of some of the bright lines seen in flames of some chemical elements. In other words, some of the light that some chemical elements emit are exactly the ones that are absent in the sunlight.

In 1849, the French physicist, Léon Foucault made a crucial discovery. More precisely speaking, it was known that the double D-lines in the solar spectrum coincide with the bright lines emitted by an electric arc charged with sodium salts. He passed the sunlight through the arc and found out that the double D-lines were darker. Then, he performed another experiment. Instead of the sunlight, he used the light from glowing charcoals. Originally, the charcoal light didn't have the double D-lines as the sunlight did. However, when he passed it through the arc charged with sodium salts, the dark double D-lines appeared at the positions they should!

However, Foucault's discovery was not well-known until the German physicist Gustav Kirchhoff repeated a similar experiment with the German chemist Robert Bunsen independently from Foucault in 1859. Instead of charcoal light, they used limelight, a type of stage lighting often used in theaters in the 19th century, which is suitable just like charcoal light because it doesn't have the double D lines as well. They let the limelight pass through the flame of cooking salt (the main ingredient of cooking salt is sodium) and found out that the double D lines appeared! They performed another experiment. In the solar spectrum, there are no dark lines that correspond to Lithium's bright lines. When they let the sunlight pass through the flame of Lithium, the dark lines appeared at the place where Lithium's bright lines should appear! So, it was clear that the same chemical elements make both the bright lines and the dark lines at the same position (i.e., wavelength) in the spectrum. Therefore, Kirchhoff and Bunsen correctly concluded that sodium must be present in the Sun. They also concluded the existence of other elements, such as hydrogen, iron, magnesium and calcium in the Sun.

So, why do the dark lines appear at the wavelength where the bright lines should appear? It's because the atoms absorb the exact kind of light that they would emit in other cases. So, that kind of light is missing in the spectrum, because they are absorbed away. This is natural if you read our earlier article "Rydberg formula." When electrons move from an orbit with higher energy to a lower one, they emit the light having the difference of the two energies. When electrons move the other way around (i.e., from an orbit with lower energy to a higher one), they absorb the light having the difference of the two energies.

Kirchhoff and Bunsen also found out that the dark lines appear only when the light source is hotter than the chemical element samples. This means that only in such cases can the samples absorb energy from the light source, which is natural as colder objects absorb energy from hotter objects. Kirchhoff thus concluded that the outer part of the Sun, where the various elements were assumed to be present should be less hot than the interior of the Sun.

When the first solar eclipse after the breakthrough of Kirchhoff and Bunsen, happened in India on August 18, 1868, many scientists came there to analyze the spectrum of the sunlight. As the Sun is covered by the Moon during the solar eclipse, they could clearly see the "prominence" and the "corona," recently discovered. See Fig. 2 for a photo of the Sun during a solar eclipse. Corona is white and prominence, the flame extended from the surface of the Sun is red.

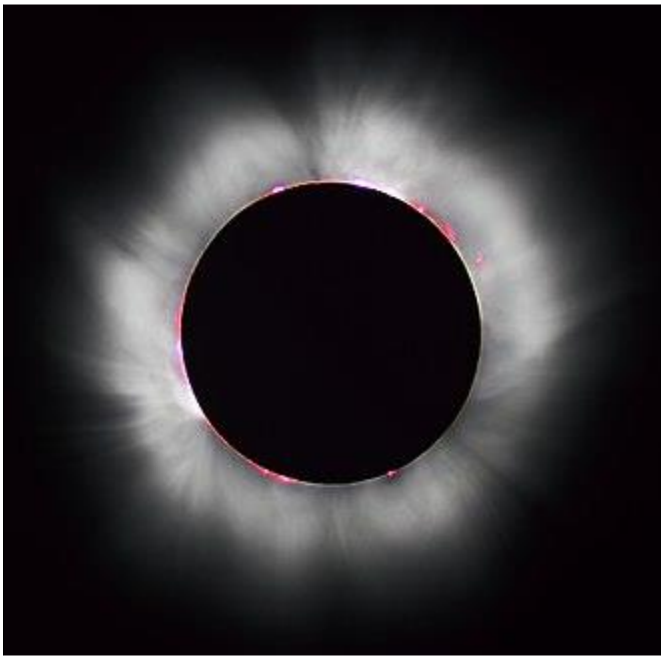

Fig. 2. corona and prominence visible during the solar eclipse

(Image credit: Luc Viatour, https://Lucnix.be)

They found out that the spectrum of prominence were bright lines. This means that the prominences were glowing gases. From the bright lines, they could find out that prominence was mostly made out of hydrogen. The French astronomer Jules Janssen also realized that prominence was so bright that a solar eclipse is not needed to observe the spectrum of bright lines as long as he observed the rim of the Sun. Right on the next day, he went on to observe the Sun for some weeks. He found a new line that had never been observed from the elements on the Earth. This line was so closely located to the double D lines that other astronomers did not know that it was a new line. In October, the English astronomer Norman Lockyer made the same discovery as Janssen. So, this means the presence of a new element in the Sun. It was named "helium" as the Greek word for the Sun is ἥλιος (helios). In 1881, the Italian physicist Luigi Palmieri observed the spectrum line of helium from material recently erupted from the volcano, Mount Vesuvius. In 1895, the Scottish chemist Sir William Ramsay succeeded in isolating helium, which is a gas. In 1904, he received the Nobel Prize in chemistry for discovering helium and other gases.

Summary

- The same chemical element can produce both dark lines and bright lines depending on the situation. The wavelengths of the dark lines and the ones of the bright lines are same because atoms absorb the same kind of light that they emit.
- In the spectrum of the sunlight, there are some dark lines. From the positions of the dark lines (i.e., wavelengths), we can deduce which elements are present in the Sun.
- Helium was first discovered this way. It was later found on the Earth.