Production of Light

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When light is passed through a prism or a diffraction grating to produce a spectrum, the type of spectrum you will see depends on what kind of object is producing the light: is it a thick or thin gas, is it hot or cool, is it a gas or a solid? There are two basic types of spectra: continuous spectrum (energy at all wavelengths) and discrete spectrum (energy at only certain wavelengths). Astronomers usually refer to the two types of discrete spectra: emission lines (bright lines) and absorption lines (dark lines in an otherwise continuous spectrum) as different types of spectra.

Continuous Spectrum

A rainbow is an example of a continuous spectrum. Most continuous spectra are from hot, dense objects like stars, planets, or moons. The continuous spectrum from these kinds of objects is also called a thermal spectrum, because hot, dense objects will emit electromagnetic radiation at all wavelengths or colors. Any solid, liquid and dense (thick) gas at a temperature above absolute zero will produce a thermal spectrum. A thermal spectrum is the simplest type of spectrum because its shape depends on only the temperature. A discrete spectrum is more complex because it depends on temperature and other things like the chemical composition of the object, the gas density, surface gravity, speed, etc. Exotic objects like neutron stars and black holes can produce another type of continuous spectrum called ``synchrotron spectrum'' from charged particles swirling around magnetic fields, but I will discuss them in another chapter later on. For now, let's look at a thermal spectrum.

Sometimes astronomers use the term ``blackbody'' spectrum for a thermal spectrum. A ``blackbody'' is an object that absorbs all the light falling on it, reflecting none of it, hence, it appears black. When the ``blackbody'' object is heated, it emits light very efficiently without any gaps or breaks in the brightness. Though no object is a perfect ``blackbody'', most stars, planets, moons and asteroids are near enough to being ``blackbodies'', that they will produce spectra very similar to a perfect thermal spectrum.

Some thermal spectra for objects of different temperatures are illustrated in the figure below.
Some key features of a thermal (continuous) spectrum are as follows:

1. There is light from a dense object at all possible $\lambda IF$ the object is above 0 K (absolute zero). Since everything in the universe is above 0 K, all dense objects (solids, liquids, thick gases) will produce a thermal spectrum.

2. The shape of a continuous spectrum depends on only the temperature of the object NOT its chemical composition. This allows you to determine the temperature of an object from a great distance away.

3. As the temperature of an object increases, more light is produced at all wavelengths than when it was cooler. You can see this effect with a light bulb wired to a dimmer switch. As you raise the current going to the bulb, the bulb's filament gets hotter and brighter.

4. As the temperature of an object increases, the peak of thermal spectrum curve shifts to smaller wavelengths (higher frequencies)---cool things appear red or orange, hotter things appear yellow or white, and very hot things blue or purple. This is opposite to what artists use for "cool" colors (blues) or "hot" colors (reds)! You can also see this effect with the light bulb wired to a dimmer switch. The dim bulb will have an orange color and as you make it brighter, the bulb will turn yellow and even white.
Wilhelm Wien (lived 1864--1928) discovered that the peak of the thermal spectrum curve, $\lambda_{\text{peak}}$, is related to the temperature by $\lambda_{\text{peak}} = 2.9 \times 10^6$ nanometers / temperature (in K). This simple relation is now known as **Wien's Law**. Using this you will find that cool objects like cars, plants, and people radiate most of their energy in the infrared. Very cold objects radiate mostly in the radio band.

A small change in the temperature produces a HUGE change in the amount of energy emitted by every unit area of the object. If you add up all of the energy emitted every second by an area of one square meter on the object's surface, you find it equals $\sigma \times \text{temperature}^4$, where $\sigma$ is another universal constant of nature [$= 5.67 \times 10^{-8}$ J/(m$^2$ K$^4$ s)]. This relation is called the **Stefan-Boltzmann** law. Because the
temperature is raised to the fourth power, a small rise in the temperature of an object will produce a
HUGE increase in the amount of energy it emits.

When you add up all of the energy of all of the square meters on the object's surface, you get the
**luminosity**---the total amount of energy emitted every second by the object. The luminosity = (total
surface area) × (σ×temperature⁴). If our Sun were just twice as hot as it is now, it would produce 2⁴ = 16
times more energy than it does now!

### Discrete Spectrum

Close examination of the spectra from the Sun and other stars reveals that the rainbow of colors has many dark
lines in it, called **absorption lines**. They are produced by the cooler thin gas in the upper layers of the stars
absorbing certain colors of light produced by the hotter dense lower layers. You can also see them in the
reflected light spectrum from planets. Some of the colors in the sunlight reflecting off the planets are absorbed
by the molecules on the planet's surface or in its atmosphere. The spectra of thin (low density) gas clouds are a
series of bright lines called **emission lines**. In both of these types of spectra you see spectral features at certain,
discrete wavelengths (or colors) and no where else.

![Absorption line spectrum](image1.png)

![Emission line spectrum](image2.png)

Two ways of showing the same spectra: on the **left** are pictures of the
dispersed light and on the **right** are plots of the intensity vs. wavelength.
Notice that the pattern of spectral lines in the absorption and emission
line spectra are the **same** since the gas is the same.
The type of spectrum you see depends on the temperature of the thin gas. If the thin gas is cooler than the thermal source in the background, you see absorption lines. Since the spectra of stars show absorption lines, it tells you that the density and temperature of the upper layers of a star is lower than the deeper layers. In a few cases you can see emission lines on top of the thermal spectrum. This is produced by thin gas that is hotter than the thermal source in the background. Unlike the case for absorption lines, though, the production of emission lines does NOT require a thermal source be in the background. The spectrum of a hydrogen-emission nebula ("nebula" = gas or dust cloud) is just a series of emission lines without any thermal spectrum because there are no stars visible behind the hot nebula. Some objects produce spectra that is a combination of a thermal spectrum, emission lines, and absorption lines simultaneously!

What is very useful about discrete spectra is that the pattern of lines you see depends on the chemical composition of the thin gas. Each element or molecule produces a distinct pattern of lines—each element or molecule has a "fingerprint" you can use to identify it. This allows you to remotely determine what stars, planets, nebulae, etc. are made of!

The composition cannot be found from just one line because one element may have one spectral line at the same wavelength as another element's spectral line. However, an element's pattern of lines is unique. Using a single line to identify a gas would be like identifying the name of someone using just one letter of their name—many people will have that same letter in their name, but the pattern of letters (which letters and how they are arranged) is unique to that one person. Of course, stars, planets, nebulae, etc. are made of more than one type of material, so you see the discrete spectra of many elements and molecules superimposed on each other—all of the spectral lines add together. An experienced astronomer can disentangle all the different patterns and sort out the elements and molecules (but it does take time!).

**Vocabulary**

- absorption line spectrum
- emission line spectrum
- continuous spectrum
- luminosity
- discrete spectrum
- Stefan-Boltzmann law
**formulae**

1. **Wien's Law**: \( \lambda_{\text{peak}} = 2.9 \times 10^6 \text{ nanometers/temperature} \). The units of the wavelength are nanometers and the temperature is in Kelvin (K).

2. **Stefan-Boltzmann Law**: Energy emitted by a square meter on an object's surface = \( \sigma \times \text{temperature}^4 \), where \( \sigma \) is a constant of nature.

**review questions**

1. What are the three basic kinds of spectrum? Can an object produce more than one type at the same time?

2. What produces a **thermal spectrum**? Does it depend on chemical composition?

3. How can temperature be determined from a continuous spectrum? How would the color of a hot object compare to the color of a cooler object? At what wavelength do you at 98.6 degrees Fahrenheit radiate the most? (Hint: use the temperature scales table.)

4. How will the **thermal spectrum** produced by a chunk of lead compare to the thermal spectrum produced by a chunk of iron of the same size and temperature?

5. What produces an **emission line spectrum**? Do you need a thermal source in the background?

6. Can you see emission lines if a thermal source is in the background? What does their visibility depend on? (Think about the temperature of the gas producing the emission lines and the temperature of the background thermal source.)

7. What produces an **absorption line spectrum**? Do you need a thermal source? Would you see absorption lines if the gas in front of a thermal source was hotter than the thermal source? Explain why.

8. Why must you use a **pattern** of lines to find the composition? Why is one line not sufficient?

9. What kind of spectrum and what pattern of lines would you see if you heated up a tube filled with hydrogen, helium and neon gas?

**Bohr atom**

Scientists have had the technology to observe discrete spectra since the beginning of the 19th century. They had to wait over a hundred years, though, for an explanation of how the discrete spectra were produced. They knew that it was produced by atoms and that atoms had negative and positive charges in them. Some models of the atom were similar to our current one: the positive charges are concentrated in a central nucleus with the negative charges swarming around it, but the atoms should be unstable. As the negative charges (called **electrons**) move around the nucleus, they should radiate light and spiral into the nucleus in about 10^{-16} second. This is obviously contradicted by common experience!

*Niels Bohr* (lived 1885--1962) provided the explanation in the early 20th century. He said that the electron can be only found in energy orbits of a certain size and as long as the electron is in one of those special orbits, it would radiate no energy. If the electron changed orbits, it would radiate or absorb energy. This model sounds outlandish, but numerous experiments have shown it to be true.

In Bohr's model of the atom, the massive but small positively-charged **protons** and
massive but small neutral **neutrons** are found in the tiny nucleus. The small, light negatively-charged **electrons** move around the nucleus in certain specific orbits (energies). In a neutral atom the number of electrons = the number of protons. The arrangement of an atom's energy orbits depends on the number of protons and neutrons in the nucleus and the number of electrons orbiting the nucleus. Because every type of atoms has a unique arrangement of the energy orbits, they produce a unique pattern of absorption or emission lines.

The structure of the atom's for the two most common elements in nature.

Different elements have different number of **protons** and different layouts of their energy levels.

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All atoms with the same number of protons in the nucleus are grouped together into something called an **element**. Because the atoms of an element have the same number of protons, they also have the same number of electrons and, therefore, the same chemical properties. For example, all atoms with one proton in the nucleus have the same chemical properties and are called Hydrogen. All atoms with two protons in the nucleus will not chemically react with any other atoms and are known as Helium. The atoms called Carbon form the basis of life and have six protons in the nucleus. In the figure below, atom (a) is Hydrogen, atom (b) is Helium, atoms (c), (d), and (e) are Lithium.
Elements are sub-divided into sub-groups called **isotopes** based on the number of protons AND neutrons in the nucleus. All atoms of an element with the same number of neutrons in the nucleus are of the same type of isotope. An element's isotopes will have very nearly the same chemical properties but they can behave very differently in nuclear reactions. For example, all of the isotopes of the element Hydrogen have one electron orbiting the nucleus and behave the same way in chemistry reactions. The ordinary Hydrogen isotope has 0 neutrons + 1 proton while another Hydrogen isotope called **Deuterium** has 1 neutron + 1 proton and another Hydrogen isotope called **Tritium** has 2 neutrons + 1 proton in the nucleus. Tritium is radioactive---its nucleus spontaneously changes into another type of nucleus. In the figure above, atoms (c), (d), and (e) are different isotopes of the same element called Lithium.

Most atoms in nature are neutral, the negative charges exactly cancel the positive charges. But sometimes an atom has a hard collision with another atom or absorbs an energetic photon so that one or more electrons are knocked out of the atom. In some rare cases, an atom may temporarily hold onto an extra electron. In either case, the atom has an extra positive or negative charge and is called an **ion**. For example, the carbon ion \( \text{C}^+ \) has 6 protons and 5 electrons and the iron ion \( \text{Fe}^{2+} \) has 26 protons and 24 electrons. Because the number of electrons are different, an ion of an element will behave differently in chemical reactions than its neutral cousins. In the figure above atom (d) is a \( \text{Li}^+ \) ion [compare it with atom (c) or (e)].

In order to explain discrete spectra, Bohr found that atoms obey three basic rules:

1. Electrons have only certain energies corresponding to particular distances from nucleus. As long as the electron is in one of those energy orbits, it will not lose or absorb any energy. The energy orbits are analogous to rungs on a ladder: electrons can be only on rungs of the ladder and not in between rungs.

2. The orbits closer to the nucleus have lower energy.

3. Atoms want to be in the lowest possible energy state called the **ground state** (all electrons as close to the nucleus as possible).
How Atoms Produce the Spectra

Let's see how Bohr's model of the atom explains the three types of spectra. An emission line is produced by an atom in a "excited" energy state---the electron is not in as low an energy orbit as possible. Remember rule #3! In order to go to a lower energy orbit, the electron must lose energy of a certain specific amount. The atom releases the energy is the form of a photon with that particular energy. The energy of photon = the difference in energy of the energy orbits (energy ladder rungs).

Example: An atom with an electron at the \( E_2 \) orbit and wants to get to the lower \( E_1 \) energy orbit. It gives off a photon with energy \( E = h \times f = E_2 - E_1 \). The electron may reach the ground state in one jump or it may temporarily stop at one or more energy levels on the way, but it can NOT stop somewhere between the energy levels. Different jumps produce photons of different energies. A larger jump to a lower energy level, will produce a photon with greater energy (smaller wavelength).

The atom produces light of certain wavelengths. (Remember that light is both a photon and a wave!) The more atoms undergoing a particular transition, the more intense the emission line will be. The intensity depends on the density and temperature of the gas.

An absorption line is produced when a photon of just the right energy is absorbed by an atom, kicking an electron to a higher energy orbit. The photon had energy = the difference in energy of the energy orbits. Because the energy levels in an element's atoms are fixed, the size of the outward jumps made by the electrons are the same as the inward jumps. Therefore, the pattern of absorption lines is the same as the pattern of emission lines. Other photons moving through the gas with the wrong energy will pass right on by the atoms in the thin gas. They make up the rest of the continuous spectrum you see.

Example: An atom with electron in the \( E_1 \) orbit sees a photon with energy \( E_{\text{photon}} = E_2 - E_1 \). The photon is absorbed and electron moves to \( E_2 \). The photon is later re-emitted but in a random direction---not necessarily
in the same direction as the original photon! An observer will see less photons from the direction of the continuous source at that specific frequency (color) than other frequencies (colors). Photons of other energies pass right on by without being absorbed. The atom can absorb photons of just the right energy to move an electron from one energy level to another level. The more atoms undergoing a particular absorption transition, the darker (or "stronger") the absorption line. The strength of the absorption line depends on the density and temperature.

A thermal spectrum is produced by atoms that are closely packed together. The energy levels of the atoms are distorted by their neighboring atom's electrons. This smears out the normally sharp spectral lines (they become fatter).

Example: An orange line is fattened so that one edge is in the yellow wavelengths and the other edge is in the red wavelengths. The amount of smearing, or broadening, depends on the density. Eventually, the density gets high enough to where the smeared lines all merge together to produce the rainbow of colors of a continuous
Electromagnetic Radiation

Vocabulary

<table>
<thead>
<tr>
<th>electron</th>
<th>ion</th>
<th>element</th>
<th>ground state</th>
</tr>
</thead>
<tbody>
<tr>
<td>proton</td>
<td></td>
<td>isotope</td>
<td>neutron</td>
</tr>
</tbody>
</table>

Review Questions

1. Where are electrons, protons, and neutrons located in the atom? Can the electron be found at any position or energy in the atom?
2. How does the Bohr atom model explain emission line spectra?
3. Which produces a shorter wavelength of light: an electron jumping from the 6th to 2nd energy level, or one jumping from 3rd to 2nd energy level? Explain your answer.
4. How does the Bohr atom model explain absorption line spectra?
5. Which would produce an absorption line at a longer wavelength: an electron jumping from the 1st to 5th energy level, or one jumping from 1st to 3rd energy level? Explain your answer.
6. Which will produce a stronger absorption line: a 10,000 K cloud with 100 particles in front of a hot star or a 10,000 K cloud with 1,000,000 particles in front of a hot star? Why is that?
7. If the atom absorbs a photon and later emits it, why do we see any absorption lines at all?
8. How does the Bohr atom model explain thermal spectra?
9. How will the spectra from atoms of the hydrogen isotopes deuterium and tritium compare to the spectra of ordinary hydrogen atoms?
10. Why would you not expect the absorption lines of the calcium ion \( \text{Ca}^+ \) to be the same as the ones of neutral calcium \( \text{Ca} \)?
11. Will the hydrogen ion \( \text{H}^+ \) produce any absorption lines or emission lines? Explain your answer.

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