Light From Our Universe

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SCIE1121: Our Universe
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Expected Learning Outcomes

After this lecture you should have an understanding of the electromagnetic spectrum and the wave-particle nature of light, including how the photoelectric effect provides evidence of the quantum nature of light. You should be able to describe three emission mechanisms for electromagnetic radiation, and the formation of spectral lines.

Assessed Content:

- Describe the properties of light: describe light as a wave and light as a particle
- Describe the photoelectric effect and how it shows evidence for light behaving as a particle ('quantized nature of light')
- Describe the electromagnetic spectrum
- Describe what emission and absorption lines are and why they are discrete
- Describe the following astrophysical sources of light: 21cm HI line, blackbody radiation, synchrotron radiation

TEXTBOOK REFERENCE: Openstax Astronomy, Chapter 5: Radiation and Spectra

1 The Electromagnetic Spectrum

Light has been the primary ‘messenger’ humans have used to explore our Universe. For most of human history, we have been able to only use the parts of the electromagnetic spectrum that we can perceive using our eyes: visible light. However, visible light makes up only one tiny part of the electromagnetic spectrum.

What are some of the properties of light (which I will use interchangeably to mean ’all electromagnetic radiation’. When I mean ’visible light’ I will use either that term or ’optical light’)? We observe light to carry energy - for example, light from the sun warms the Earth. The other ways in which light can carry energy are explored when we discuss the photoelectric effect a bit later on.

We also know that light travels at a constant speed in a vacuum, and that nothing can travel faster than light. The finite speed of light can be derived from Maxwell’s equations (a set of physical equations that describe how electric and magnetic fields work).

We also know that light can be absorbed and emitted. The emission and absorption of light by different atoms tells us something about the quantum nature of the world on the atomic scale (everything moves in discrete jumps, not continuously).

Light travels in a straight line, but can bend when passing into a different medium (e.g. in water), and can reflect, diffract and interfere, just like all other kinds of waves. However, sometimes light behaves more like a billiard ball. Some of the phenomena exhibited by light can be explained satisfactorily by both the wave and particle model (e.g. reflection and refraction), however sometimes light behaves only like a wave (diffraction) or only like a particle (the photoelectric effect). We also know that a particle of light has no mass.

In this lecture we will explore the electromagnetic spectrum, the wave-particle duality of light and some phenomena that you will need to understand if you want to use electromagnetic radiation as a ’messenger’ to learn about our Universe.

1.1 NOT ASSESSED: Light follows the curvature of space-time

One of the first things you learn about light is that it always travels in straight lines: we cannot see around corners, for example. However, the definition of something being a 'straight line' depends on the underlying geometry of space.

Einstein's general theory of relativity tells us that matter can cause 'space-time' - the surface over which light moves - to bend and warp. Light will follow straight lines (called 'geodesics') across this bent surface. To us, it can look like light 'bends' around massive objects. An example of this is in galaxy lensing. A large foreground galaxy has enough mass to make space-time bend, so light from a galaxy directly behind it is warped and bent around the foreground galaxy. Consequently, we see the background galaxy in this 'lensed' image.

1.2 NOT ASSESSED: Representing a wider range of frequencies - can we believe false color images?

One of the learning outcomes of this lecture is to understand some of the ways in which electromagnetic radiation beyond visible light is emitted by astrophysical objects. To illustrate this in my slides and in these notes I will present you with several images that I will tell you show radio wave emission, or gamma-ray/x-ray emission. These are examples of 'false color' images.

You will already be familiar with false color images without realizing it. For example, rain radar maps are actually mapping where radio emission is being reflected by moisture and rain in the atmosphere. Of course, we can't 'see' radio waves so the intensity of the radio waves are represented by different colors (green to mean little reflection or light rain, and red to represent lots of reflection or heavy rain).

The same is done in astronomy. Sometimes we will represent different frequencies of electromagnetic radiation with different colors. For example, a composite image of a nebula may have spectral lines represented by different colors (red for Hydrogen, green for oxygen).

If we make an image of an astrophysical object with only one (or a finite range) of frequencies, sometimes we use colors to represent brightness.

For example, we may represent bright or intense radio emission at 21 cm wavelengths with a yellow or white color, and fainter, more diffuse emission with reds or browns.

Usually the images will make it clear whether they are remapping different wavelengths to colors we can perceive, or whether they are an intensity map for one single frequency or frequency band. False color images often highlight features we may otherwise miss or not be able to see. They are not necessarily misleading, but a sort of shorthand for representing reality.

2 Light as a wave

Many of the observed properties of light are consistent with it being a wave phenomenon. That is, if you are familiar with the effect in, say, sound waves of water waves, the phenomenon also exists for light. This includes reflection, refraction and diffraction.

Light waves travel at a constant speed (in a vacuum), and this speed can never be exceeded. The speed of light c is a physical constant: $c = 2.998 \times 10^8$ ms^{-1}, usually rounded up to the more familiar $c = 3 \times 10^8$ ms^{-1}.

The frequency and wavelength of an electromagnetic wave are related to one another, and to the speed of light. The frequency ν of an electromagnetic wave with wavelength λ is

$$\nu = \frac{c}{\lambda}$$

In astronomy, the wave nature of light is used to describe low-frequency electromagnetic emission: radio waves, infra-red emission and, in most applications, optical light.

2.1 What is waving?

When it comes to a wave on a string, or a wave in water, it is very clear what is doing the waving. But what about light?

Maxwell's equations are a set of equations written down by the Scottish physicist James Clark Maxwell in 1865. Maxwell's equations can be used to describe all electromagnetic phenomena: from how like charges repel and opposites attract, why magnets always have two poles and not one, to describing the propagation of electromagnetic waves.

When they are solved (something we won't ask you to do, although if you are curious then consider studying electromagnetism at more advanced levels), Maxwell's equations can describe a wave that propagates through space at the speed of light c. An electromagnetic wave is made up of oscillating electric and magnetic fields, perpendicular to one another and to the direction of travel (figure ref). The electric and magnetic field, and the propagation direction of an electromagnetic wave are described in physics terms as 'mutually perpendicular'.

2.2 NOT ASSESSED: Why the speed of light is fixed, and what would happen if it was different

The speed of light is usually described as being a universal constant. This is true, but have you ever wondered why the speed of light is what it is? Why doesn't the speed of light explicitly show up in Maxwell's equations?

The speed of light is related to how well free space allows electric and magnetic fields to permeate, for want of a better description. This is governed by two constants: the permittivity of free space (ϵ_0, how easy it is for the electric field to propagate) and the permeability of free space (μ_0, how easy is is for the magnetic field to propagate). If you look at Maxwell's equations, you will see these two constants.

When Maxwell's equations are solved to find a wave equation that describes the propagation of light, you find that these two constants combine together to give $c = 1/\sqrt{\epsilon_0 \mu_0}$ - the speed of light!

If these constants were just a little different, it would have a huge impact on our universe. Physicists have simulated what would happen in a universe where these constants differ a little.

3 Light as a particle

Light exhibits a phenomenon called 'wave particle duality'. This means that in some applications, light behaves like a wave, and in others like a particle - a massless billiard ball pinging around the universe.

The first description of light as a particle was made by Max Planck, a German physicist, in 1905. Planck theorized that the amount of energy carried by light came in discrete packets, or 'quanta'. These days we know Planck's quanta by the name 'photon'.

Photons carry a discrete amount of energy: each photon has an energy E that depends on the frequency (or equivalently using the equation above, wavelength). The energy of the photon and the frequency of the light are related by the equation

$$E = h\nu$$

where h is Planck's constant (a very small yet very significant number, $= 6.62 \times 10^{-34}$ Js and ν is the frequency of the light.

Some of the phenomena exibited by light can be explained by both the wave and particle nature of light, for example refraction. On the other hand, some phenomena can only be described by the particle nature of light. One example that requires us to consider the particle nature of light is the photoelectric effect.

In astronomy, we often use photons to describe phenomena associated with high-energy electromagnetic radiation, including gamma-rays and x-rays. In some applications, particularly in understanding how CCDs work, we also use photons to understand how optical light is observed by detectors.

4 Wave-Particle Duality

Light is said to exhibit a property called 'wave-particle duality': light can be explained by both the wave and particle model described above.

Different phenomena can be explained by either the wave or particle model, and some by both: interference, diffraction and polarization are all phenomena exhibited by waves and cannot be explained by single photons (e.g. photons cannot interfere with one another, or diffract/bend around

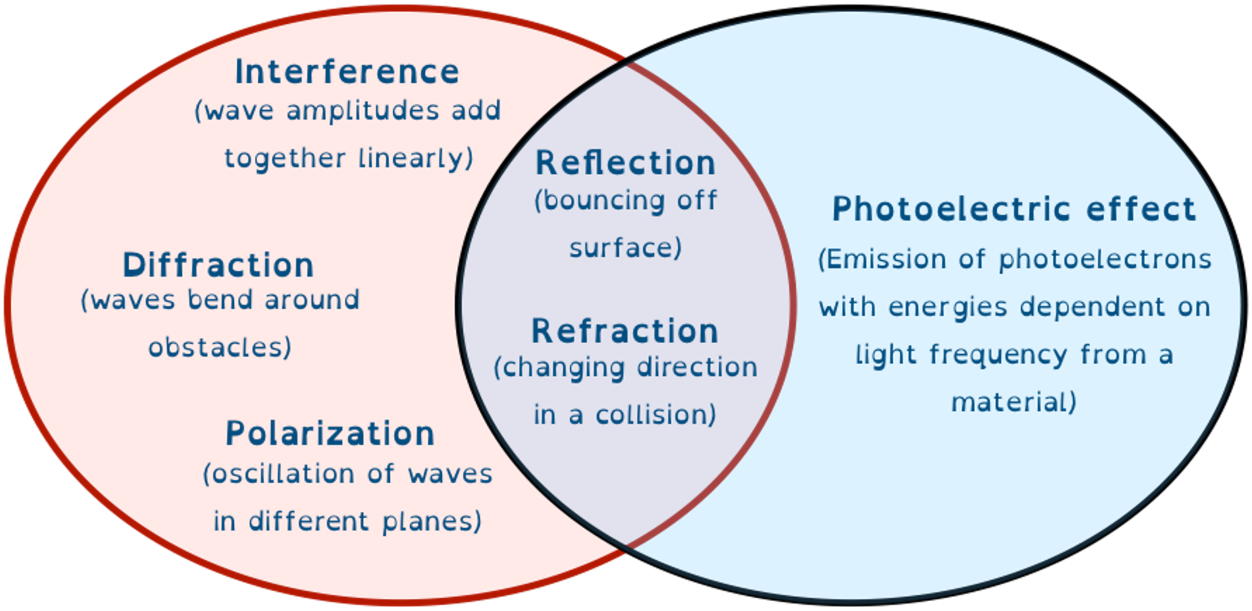

Figure 1: Venn diagram showing properties of light that are explained by the wave model of light, the particle model of light, or both. Interference, diffraction and polarization can only be explained by the wave model, reflection and refraction by both the wave and particle model and the photoelectric effect only by the particle model.

an obstacle), whereas reflection and refraction can be explained by either the wave or particle model of light.

The main challenge to the wave model of light came from a phenomenon called the photoelectric effect, which can only be explained using the particle model of light.

5 The Photoelectric Effect

5.1 Description of the photoelectric effect

The photoelectric effect is the observation of the emission of electrons from a material (usually a metal) when light is incident on the material. Electrons that are emitted in this way are known as 'photoelectrons'. The energy of each photoelectron depends on the wavelength (or frequency) of the incident light. The effect was first observed during the 1800s but was not explained until 1905, when Einstein used the quantum description of light to understand the experiment.

5.2 Contradicting the wave model of light

The photoelectric effect contradicts the classical model of light propagation. The energy of the electrons that are ejected by the photoelectric effect is independent of the intensity of the light being used. That is, a brighter source of light will increase the *number* of electrons emitted from a surface, but the energy of each individual electron stays the same.

This contradicts the classical wave model of light. If light behaved like a wave in the photoelectric effect, brighter light with a higher intensity has a larger wave amplitude, and is therefore expected to have more energy (for example, a 2m wave would impart more energy than a 1m wave if you were to stand in the break zone at the beach. If you attempt this experiment you do so at your own risk). This means that the ejected electrons would be expected to have more energy per electron.

Another observation of the photoelectric effect is that the energy of the ejected electron changes as a function of the wavelength (frequency) of light applied. The shorter the wavelength (and the higher the frequency) the higher the energy of the photoelectrons. It was also observed that for some wavelengths (frequencies) of light, no photoelectrons are emitted. The wave model of light cannot explain this phenomenon, as in the classical model the amount of energy carried by a wave (the amplitude) is independent of the wavelength (or equivalently frequency) of the light.

5.3 Einstein's Solution: 1921 Nobel Prize

Einstein found that this puzzling phenomenon could be resolved if light came in the discrete packets described by Planck - quanta we now know as photons. Recall from above that the energy E of a photon is

$$E = h\nu.$$

In this model, we can see that the energy of a photon is proportional to the frequency of light: higher frequency light equals more energy per photon.

This explains the phenomenon of how higher frequency light produces higher energy photoelectrons than lower frequency light.

Each material also has it's own unique 'work function' - this is a value related to the composition of the material that says how much energy it takes to eject a photoelectron from a material. If the amount of energy in a photon does not exceed the work function, then a photoelectron cannot be ejected. If the amount of energy in the photon does exceed the work function, then a photoelectron is ejected with an energy of incoming photon energy - work function.

The fact that the intensity of the light increases the number of ejected photoelectrons can also be understood in this model: More intense light has a greater number of photons (but all those photons will have the same energy, dependent on the wavelength of the light). If each photon liberates one electron, then more photons in equals more electrons out!

Einstein's explanation of the origin of the photoelectric effect saw him awarded the 1921 Nobel Prize for physics, for 'his services to theoretical physics, and especially for his discovery of the photoelectric effect'. While he won the prize in part for his services to theoretical physics, he never explicitly recieved a Nobel Prize dedicated to his most famous work: the General and Special theory of relativity!

6 Propagation of Light

Light is usually emitted isotropically - equally in all directions. You can imagine light emitted from a star spreading out in a sphere around the star.

As the surface of this sphere gets larger, the same intrinsic amount of light is spead over a larger area. Consequently the intensity of the light observed decreases as the square of the distance from the source.

This relationship is called the 'inverse square law' and is the basis of many calculations in astronomy where we wish to know the intrinsic brightness of a source (how bright something is irrespective of how far away it is). In the next lectures when we look at how stars evolve, we will find that just because a star is dim does not mean it is very far away! It may just be an intrinsically faint star close to us.

Figure 2: L: the INTEGRAL space telescope, with people for scale. This photo was taken in 2002 while INTEGRAL's Flight Module being prepared in ESTEC's facilities in Noordwijk, the Netherlands. INTEGRAL is a gamma-ray telescope. Image credit: ESA - A. Van Der Geest R: the Stratospheric Observatory for Infrared Astronomy (SOFIA) telescope. The telescope is mounted in the back of a Boeing 747. Flying high above most of the water vapour in the atmosphere enables SOFIA to observe IR radiation.

The inverse square law is important for astronomers who work on the Cosmic Distance Ladder, which you may remember from your earlier lectures.

7 Observing the electromagnetic spectrum

Astronomers use electromagnetic radiation to understand many different things about our Universe, right from deducing that the Universe started with the Big Bang to theorising about how the Universe may end.

One major challenge for astronomers is the Earth's atmosphere. While the atmosphere may protect us from gamma-rays and x-rays from outer space, astronomers who try to look at the universe in these wavelengths must use telescopes in space. The same is true for UV radiation and microwaves - UV astronomers reply on space-based telescopes as the majority of UV radiation is blocked by the Ozone layer. Infra-red and microwave observations can be made from places that have low atmospheric moisture content (as moisture absorbs IR and microwave radiation) or even from high in Earth's atmosphere from aeroplanes. The flyiung SOFIA observatory uses a Boeing 747 jumbo jet to observe IR radiation from space.

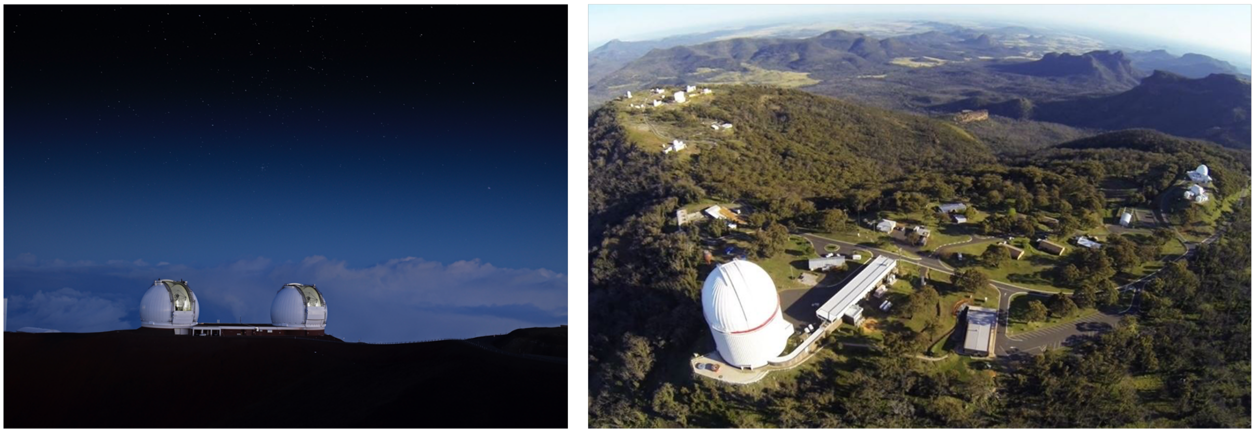

Figure 3: L: The twin 10m Keck telescopes on top of Mauna Kea, Hawai'i. These telescopes are used to study everything from exoplanets to distant galaxies. The round white domes each housing one 10m telescope are shown at sunset Image Credit: W. M. Keck Observatories R: Closer to home is Siding Spring Observatory in NSW. The Anglo-Australian Telescope is the largest optical telescope in Australia, with a 4m diameter. Many white buildings containing telescopes are visible in the green Australian bush. Image Credit: CC

For optical astronomers, the only thing that stands between them and the Universe is cloud cover. This is why most optical observatories are located in places that have a small number of days per year where the sky is cloudy. For example, observatories in Chile (Las Campanas and Paranal) and Hawai'i (Mauna Kea) are built on top of mountains that are above the cloud layer.

Luckiest of all are radio astronomers, who are not affected by clouds! Radio waves can permeate through not just the atmosphere but even thick cloud cover. This means that radio observatories can operate day and night, in almost all weathers (although sometimes the large radio dishes are stowed in high winds).

How well radiation can permeate the atomosphere can be described by a 'transmission curve', a way of describing how much of the radiation is transmitted through the atmosphere, and how much is absorbed.

8 Astrophysical Objects in Different Wavelengths

Most astrophysical objects emit radiation across the electromagnetic spectrum. Different physical processes that occur in these objects will mean that the object may look different at different wavelengths

8.1 Sun

In optical light, the Sun looks relatively featureless and smooth. However, if you look at the sun in the infra-red, you can see many light and dark patches. Dark patches are cooler areas, while the brigher areas are the hottest parts. IR emission from the sun comes from the surface layers of the sun. The dark spots are sometimes so cool that they do not emit optical light, and we can observe them as sunspots.

In UV the sun looks slightly fuzzy - this is because most of the UV emission from the sun is coming from the outermost layers of the sun (the corona) which are the hottest part. Compare the image of the sun in the UV to the image in the infrared - notice how the dark patches on the IR image correspond to the brightest parts of the UV image. This is because the magnetic fields associated with the sunspots heat and twist the solar plasma and eject it out into the Sun's corona, where it glows brightly in the UV.

A similar phenomenon can he seen in the x-ray image of the sun. Here the sun looks even fuzzier - this is because the whole corona is glowing brightly in x-rays that are produced by plasma that has been heated to $\sim 10^8$ K. In the x-ray image you can begin to see the filamentary structure of the corona.

9 Spectral Lines

All atoms have a unique fingerprint of spectral lines that they emit or absorb. This is a consequence of the quantization of the electron energy levels in an atom. Take the hydrogen atom as an example: this is the simplest atom comprised of a proton and an electron.

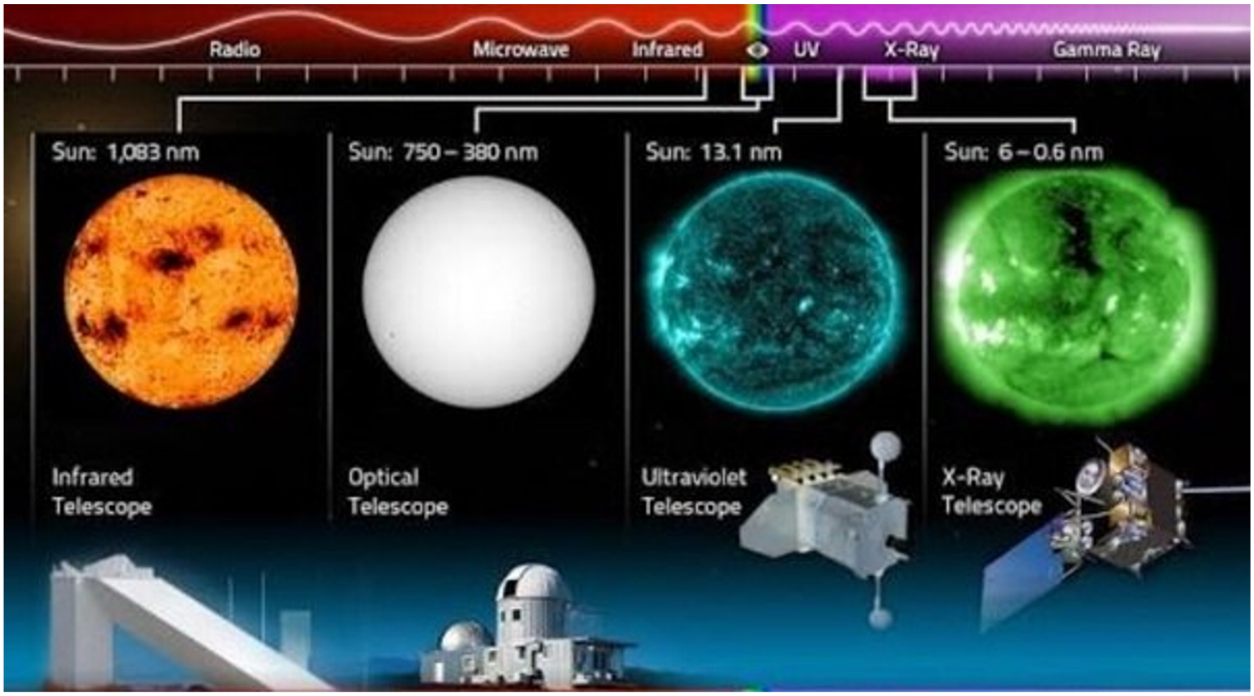

Figure 4: Images of the sun in different wavelengths (L-R: IR, Optical, UV and X-Ray). L: Brightness of IR radiation is represented in a yellow color. The sun has many dark, cool patches which emit less IR radiation. Next: In optical light the sun appears as a featureless, smooth disk. There. is a small blemish on it's face corresponding to the darkest patch on the IR image. Next: In UV, the sun is shown as a dark blue with glowing cyan edges, where the upper photosphere and corona emit lots of UV light. R: In X-Rays, the sun is represented as green. It has diffuse edges that arise from the outer corona - the hottest part of the sun - emitting x-ray radiation.

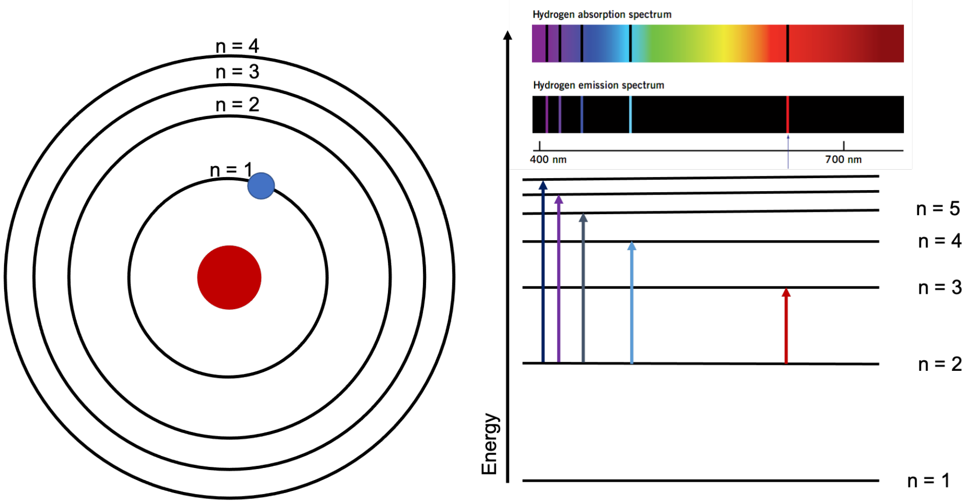

Figure 5: L: The Bohr model of the atom, developed by Danish physicist Niels Bohr, shows how the quantization of energy levels that an electron can occupy gives rise to spectral lines. In this model we see the hydrogen atom, a proton surrounded by discrete, concentric circles that represent energy states the electron can inhabit. In the image the electron is in the smallest circle - the ground state. R: Representation of electron energy levels. Shown are the electron transitions that give rise to the Balmer series of spectral lines, where electrons transition to or from the n = 2 energy level. The Balmer series is used in optical astronomy to measure the age and temperature of stars and stellar populations. Arrows between the second and each subsequent energy level are shown, representing the transitions that give rise to the Balmer series.

The hydrogen atom's electron can only hop between energy levels that are determined by the structure of the atomic nucleus. To transition between energy levels, the electron must absorb or emit a photon (energy packet) with an energy of exactly the difference between the energy levels. This quantization of the emission and absorption of energy by atoms leads to the formation of a characteristic spectrum that is like a fingerprint for each individual atom.

Atomic energy levels are numbered. $n = 1$ is the 'ground state' - the lowest energy level an electron can occupy.

10 Emission vs. Absorption Lines

10.1 Emission Lines

Emission lines form when an electron moves from a higher energy level to a lower energy level by emitting a photon. This photon is observed as emission of light with a frequency of $\nu = E/h$, where E is the difference in energy between the two energy levels.

The most famous emission line series is the Hydrogen Balmer line series. These emission lines come from transitions where the electron drops down into the $n = 2$ energy level.

Have you ever noticed that old street lamps are all the same characteristic yellow-orange color? This color comes from a transition in sodium atoms that produces two closely-spaced emission lines called the ‘sodium D line’.

10.2 Absorption lines

Absorption lines for when an electron moves from a lower energy level to a higher energy level by absorbing a photon. Because only photons with energies that are precisely the difference between these two energy levels can be absorbed, this gives rise to a spectrum that is ’missing’ only the frequencies of light that were absorbed. This is observed as dark bands in an otherwise continuous spectrum.

Absorption spectra form in astrophysical objects when light from a background object, with a continuous spectrum, is absorbed by some foreground gas. For example, absorption lines can be used to characterise exoplanet atmospheres, as light from the background star passes through the atmosphere in an exoplanet giving rise to an absorption spectrum.

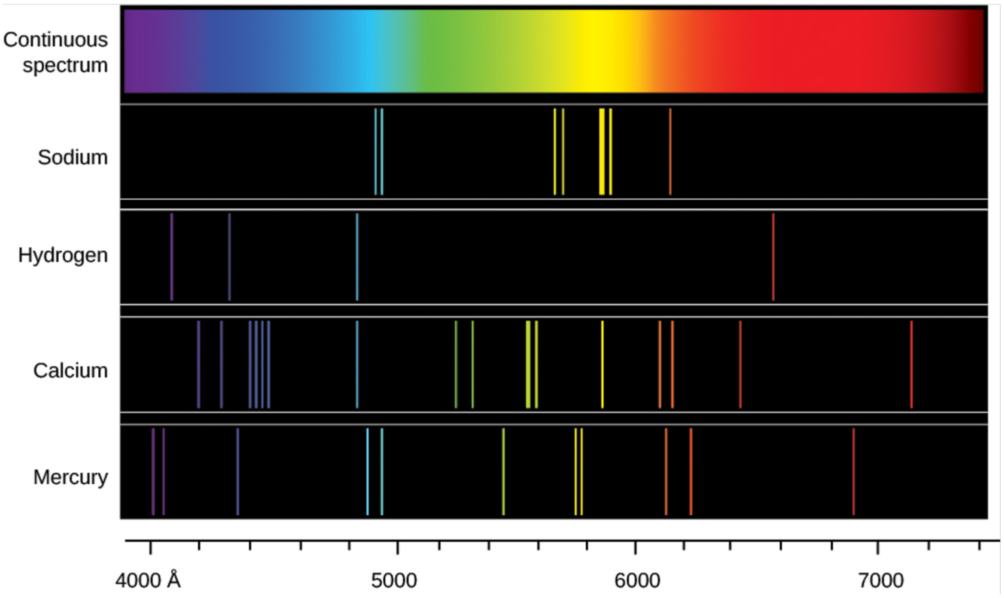

Figure 6: Examples of the emission spectra of several different atoms: sodium (used for old-fashioned orange streetlamps), hydrogen, calcium and mercury (often used to calibrate scientific instruments that measure spectra). The more electrons an atom has (the further down the periodic table it is) the more complex the spectra. Can you describe what the absorption spectra of each of these elements would look like? Complex emission line spectra are used by astronomers to calibrate some telescope instruments, as all these lines are well defined and do not change.

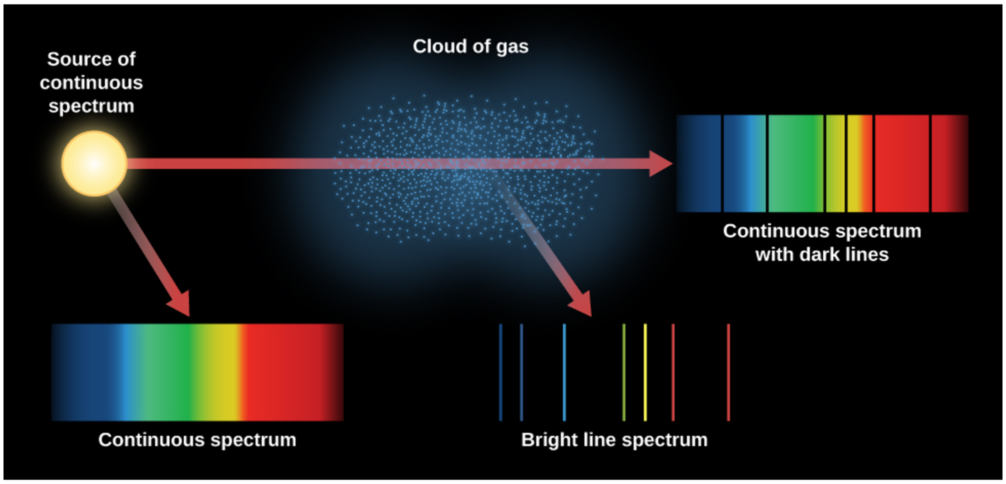

Figure 7: How absorption and emission spectra may form in astrophysical scenarios. Sources like stars emit continuous spectra. When this light passes through interstellar gas clouds, the atoms in the gas will absorb frequencies of light that excite electron transitions. When the electrons that have jumped into higher energy levels lose energy and relax back into the ground state, they emit bright emission lines. Usually the exact transitions that occur to create the absorption lines are different to the ones that occur to produce the line emission, or they occur on very different timescales.

11 Emission Mechanisms

11.1 21cm line of neutral hydrogen

The majority of our universe is composed of hydrogen, including the gas that exists between stars inside galaxies (the interstellar medium), and even in intergalactic space (the intergalactic medium).

In a hydrogen atom, the electron and proton can be described using a parameter called ‘spin’. Spin is also quantized into either ‘spin up’ or ‘spin down’. Because both the proton and electron have these property, even in the ground state the atom has two possible configurations: the proton and electron spins are aligned (a slightly higher energy state) or the proton and electron spins are anti-aligned (in opposite directions, a lower energy state).

When the spin of the electron flips, radiation is emitted with a frequency (and thus wavelength) related to the difference in energy between these two energy levels. This corresponds to a wavelength $\lambda = 21.1$ cm and $\nu = 1420.4$ MHz. This lies in the microwave part of the spectrum and can be observed with radio telescopes.

The probability that this transition occurs is tiny (2.6×10^{-15} s^{-1}), so we do not see it in the laboratory the way we do with other hydrogen atom transitions like the Balmer series. However, the universe is filled with so many hydrogen atoms that this transition occurs all the time!

The neutral hydrogen 21 cm line (sometimes known as the HI 21 cm line) enables us to see any structure containing neutral hydrogen in fine detail, including clouds of gas that make up galaxies. What's more, the 21cm line is not blocked by dust in the interstellar medium. This means we can peer through structures in our own Galaxy that otherwise obscure optical light, enabling us to see the Galactic center in great detail.

reionization

11.2 Thermal Radiation

Blackbody, or thermal radiation is emitted by any object where the emitter is in thermal equilibrium with its surroundings. Usually this is conceptualized as the emission from an object that absorbs all radiation that falls on it. The blackbody spectrum has a characteristic shape that is determined solely by the temperature of the object doing the emitting.

The blackbody spectrum has energy emitted at all wavelengths, but depending on the temperature of the object, more radiation will be emitted at a small range of frequencies. The radiation emitted by a star is a blackbody spectrum, which peaks at different wavelengths depending on the temperature of the star: the hottest stars are blue while the coolest stars are red. Hotter objects will also emit a greater total energy flux, which is why hot, blue stars are brighter than their cool, red counterparts.

Our Sun emits a blackbody spectrum, and appears yellow. However, if you calculate where the peak of the Sun's blackbody spectrum falls you will find that it actually peaks in wavelengths we would usually consider green. So why is the Sun not green? In fact, why are no stars we see green?

This is due to a combination of two effects: the wavelengths we perceive as green account for a very small part of the optical spectrum, so most of the sun's radiation comes out at redder and bluer wavelengths.

Also the human eye is actually more optimized to see yellow, red and blue than green. Thus for us to see an object as green then it must be emitting only green light.

This is why plants are green: chlorophyll absorbs all colors except the narrow band of green wavelengths. This is the plant's way of maximising the amount of energy it can take in. We observe plants as being green because chlorophyll reflects only green light - if it also reflected some yellow and red light, plants would look more yellowish, like our Sun.

11.3 Synchrotron Radiation (non-thermal emission)

Remember when we discussed waves we said that an accelerating charge emits electromagnetic waves? This is one way in which non-thermal radiation can be emitted.

To produce synchrotron radiation, electrons (or sometimes protons) spiral around magnetic field lines in a helical trajectory. As they are constantly curving around the magnetic field line, they are accelerating and so emit electromagnetic radiation.

The electrons (or other charged particles) that produce synchrotron radiation are typically moving at relativistic energies - close to the speed of light.

The wavelength (or equivalently frequency) of the synchrotron radiation depends several factors, including the kinetic energy of the particle (it's mass and relativistic velocity) and the strength of the magnetic field. The synchrotron radiation we observe comes from the sum of the radiation produced by a large population of moving electrons (or other particles) with many different energies. This gives rise to a characteristic spectrum that can be described using a power law (if you were to plot the relationship between the flux observed at a particular frequency and the frequency on a log-log plot, it will form a straight line).

Usually we observe synchrotron radiation in the radio part of the electromagnetic spectrum, and it is emitted by any objects that produce relativistic particles, including pulsars, gamma-ray bursts and jets from black holes.

A note on this font

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