Lecture 1. A Brief History of Light

Contents

Summary. Debates over the nature of light occupied physicists for over 200 years. Specifically, the question of whether light is a wave or a particle has been of central importance. This brief history follows the first scientific studies of light to theories developed at the beginning of the 20th Century.

1.1 1676: Ole Roemer Measures the Speed of Light

The speed of light was discovered by accident by a Danish astronomer, Ole Roemer, working at the Paris Observatory in the late 17th Century [1]. Roemer was studying the orbital motion of Jupiter's four bright moons (discovered by Galileo in 1610). Every 1.77 days, Io, Jupiter's innermost moon, is eclipsed by Jupiter, disappearing behind it before reappearing on the other side. Roemer was interested in using these eclipses as a "cosmic clock" to aid in the determination of longitude for sailors. Roemer discovered anomalous variations in the timings of Io's eclipses. Whenever the earth was closer to Jupiter, the eclipse happened slightly ahead of schedule and whenever the Earth was farther from Jupiter, the eclipse happened slightly behind schedule. Roemer realized that the eclipse variations could be explained if light had a finite speed. When the Earth was far away from Jupiter, it took light longer to reach the Earth from Jupiter, thus delaying our observation of the eclipse. The velocity of light may be calcualated by simply dividing the diameter of the Earth's orbit by the total time difference in the eclipse timings.

- **Q1.** Figure 1 illustrates the orbits of the Earth and Jupiter when the Earth is closet to Jupiter (see E1) and farthest from it (E2). Roemer estimated that when the Earth was at E1, Io's eclipses arrived about 11 minutes earlier than normal, and six months later when the Earth was at E2, the eclipses were observed 11 minutes later than normal. Back in the

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[1] Cosmic Horizons: Astronomy at the Cutting Edge, edited by Steven Soter and Neil deGrasse Tyson, (New Press, 2000)

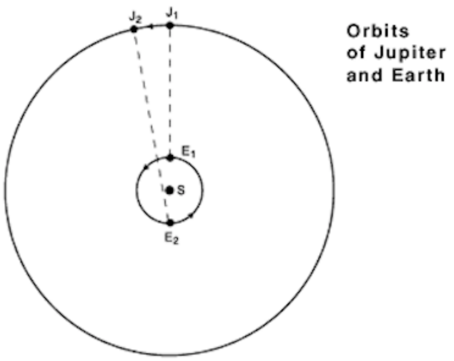

Figure 1: Solar system geometry for measuring the speed of light. Earth and Jupiter are closest at E1 and J1, and are farthest apart at E2 and J2.

> 1600's distance between the Earth and the Sun was estimated to be the equivalent of roughly 130 million kilometers. (a) calculate the speed of light (in m/s) based on this information and compare it with its modern value. (b) Use modern values for the speed of light and the Earth's orbital radius to calculate the true amplitude of the timing variations (in minutes) in Io's eclipses. How does this value compare to the 11 minutes that Roemer measured? Assume the orbits of the Earth and Jupiter are both circular.

1.2 1680: Christiaan Huygens's Wave Theory of Light

Huygens was a 17th Century Dutch physicist known best for his work in light. He developed the first mathematical theory of light as described in his 1690 work titled *Treatise on Light.* Huygens proposed that light was a longitudinal, compression wave (like sound) that propagated through a medium of perfectly elastic particles. This hypothetical medium is often referred to as the "ether."

Huygens developed a method for constructing the future shape of a wave front given its present shape. This idea is called Huygens Principle:

> Every point on a wave-front may be considered a source of secondary spherical wavelets which spread out in the forward direction at the speed of light. The new wave-front is the tangential surface to all of these secondary wavelets.

Huygens's wave theory provided a natural explanation of refraction in which the light wave slows down when it enters a denser material (like glass or water). However, because diffraction effects had not been observed for light in the 1600s, Huygens's theory provided few verifiable predictions and was largely ignored. Huygens's theory was ahead of its time.

1.3 1704: Isaac Newton's Corpuscular Theory of Light

Newton published *Principia* in 1687 in which he proposed his three laws of motion and *Opticks* in 1704, 14 years after Huygens's work. In *Opticks*, Newton rejected Huygens's wave theory of light and suggested that light was made of "corpuscles," i.e. particles, that emanated from luminous objects

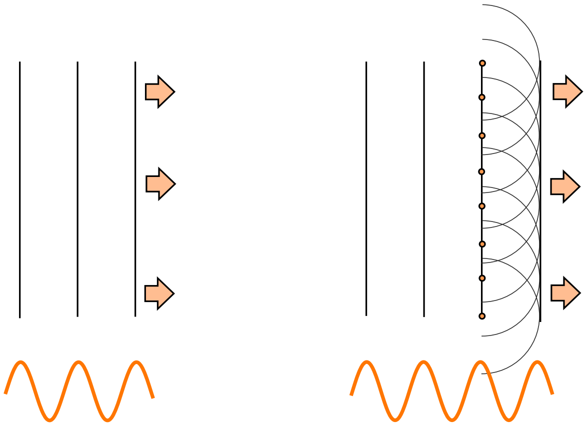

Figure 2: Illustration of Huygens's principle. A wavefront is propagated forward by placing imaginary point sources along the leading wave front.

and traveled in straight lines. Because diffraction effects had not yet been discovered, Newton's particle theory was adopted by most physicists for the next 100 years. One main disadvantage of his model was its inability to explain refraction at interfaces in a simple way.

Newton also used glass prisms to break white sunlight into a spectrum. By using a second, inverted prism, he was able to recombine the spectrum back into white light (see Figure). Newton argued that white was a composite color made up of more fundamental monochromatic colors found in the spectrum.

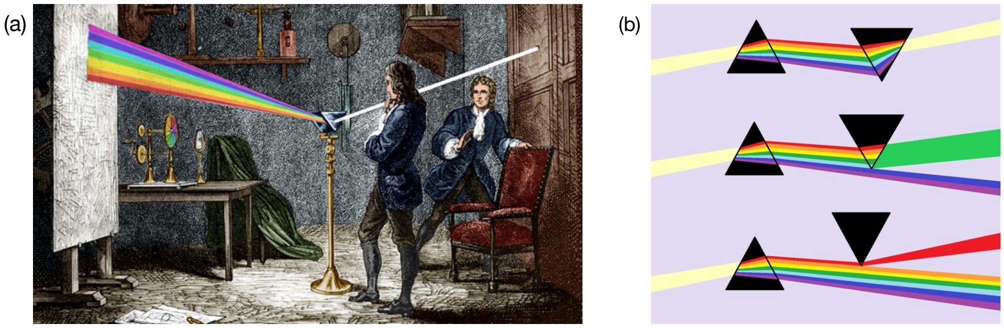

Figure 3: (a) Illustration of Newton performing his experiments with light and prisms. (b) Breaking white light into monochromatic colors and recombining combinations of colors to form non-monochromatic, composite colors.

1.4 1727: James Bradley Measures the Aberration of Starlight

Bradley was an English astronomer who discovered that the positions of stars in the sky changed depending on our motion through space. As the Earth orbits the Sun, he discovered that stars trace out small ellipses in the sky. Stars perpendicular to the Earth's orbital plane trace out circular paths with diameters around 40 seconds of arc (about 1/100 of a degree).

The discovery of aberration of starlight provides some interesting clues into the nature of light. First, consider starlight as a rain of light particles falling downward with velocity c from a star directly overhead. If the earth is moving to the right (in the $+x$ direction) with velocity u as shown in the Figure, then the relative velocity of the drops in the Earth's frame will have a horizontal component $-u$ (see Figure). In other words, the light "droplets" will appear to be coming from a location in space slightly in front of the star's true position. This is the same phenomena as running in a rainstorm. The faster you run, the more you have to hold your umbrella in front of you to avoid getting wet.

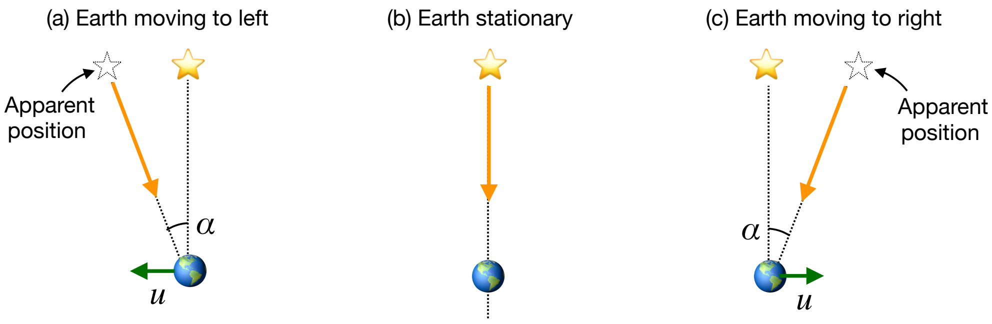

Figure 4: Aberration of starlight for a star along a line perpendicular to the Earth's motion. The star appears to move toward the direction of motion of the earth.

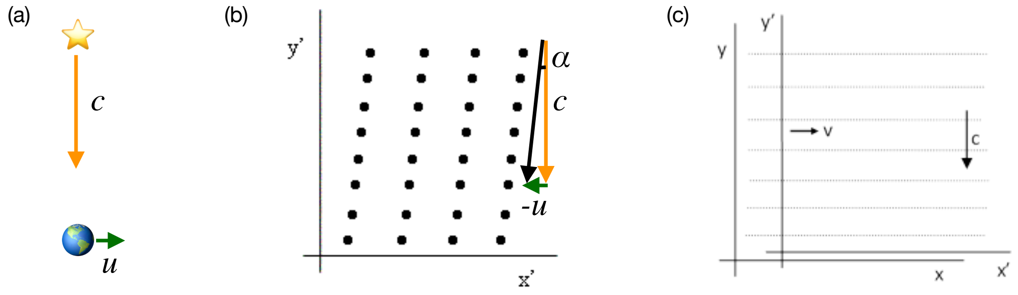

Figure 5: (a) Earth moves with velocity u perpendicular to direction of star. (b) Particle model of light. Light particles show aberration angle α in Earth's frame. (c) Classical wave model of light with ether. Light waves show no aberration assuming the Earth moves through the ether with velocity u.

In classical physics the speed of the light particles in the Earth's reference frame will be $\sqrt{u^2 + c^2}$, and the "aberration angle" will be $\alpha = \tan^{-1}(u/c) \approx u/c$.

The wave model of light predicts a different result, at least if one assumes that the ether (the hypothetical medium through which light was thought to travel) is at rest with respect to the distant star. If we assume the star is far away, the wave fronts of the light will be approximately plane-parallel. The Earth's horizontal motion will not affect the orientation of the wave fronts. Thus, the classical wave model predicts no aberration, in contradiction to Bradley's observations.

1.5 1801: Thomas Young's Double Slit Experiment

Thomas Young studied a wide variety of optical phenomena. He was troubled by several inconsistencies in Newton's theory of light corpuscles, such as why some light is transmitted at optical interfaces (e.g. an air-glass interface) and why some some is reflected. Newton's particle model offered no explanation of this effect, while analogous behaviors in water waves and acoustics did. Young designed several experiments to look for interference and diffraction phenomena in light. The culminating experiment was his famous double-slit experiment.

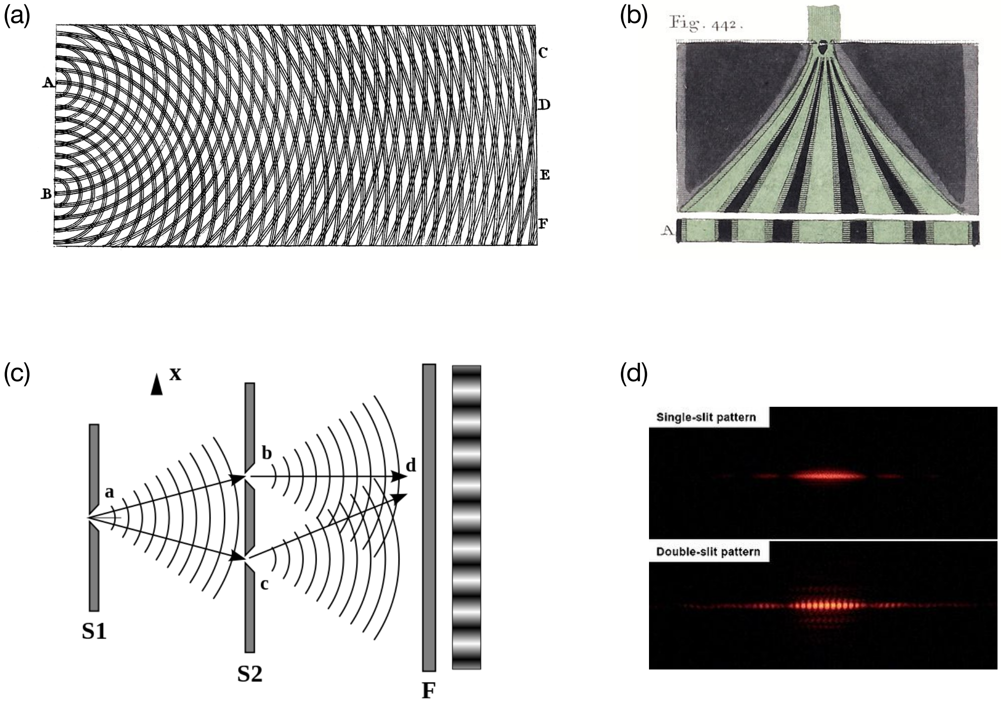

Figure 6: Double slit experiment. (a) Young's sketch of interfering water waves showing constructive and destructive zones (1803). (b) Young's illustration of interference zones using light (1803). (c) Illustration of the double-slit experiment (d) modern result of the interference and diffraction pattern produced using a single slit and a double slit.

In the double slit experiment, he created a narrow opening through which candle light entered. This narrow beam of light then illuminated two narrow slits as shown in Figure 6(c). When one slit was blocked, a broad band of light was observed on a distance screen (see Figure 6(d)). However, when both slits were uncovered, Young observed a series of dark gaps in the light band (see Figures 6(c) and 6(c)). Young realized these dark bands could be explained by destructive interference between the two light beams. Young was also able to use the spacing of the dark fringes to estimate the wavelength of the candle light. Since interference phenomena are a natural consequence of waves and since they cannot be explained by Newton's corpuscle model, Young presented his observations as evidence that light is a wave and is not composed of "corpuscles." However, due to Newton's enormous reputation, Young's work was not widely accepted.

1.6 1800-1914: The Spectrum of Invisible Rays

What we now call the electromagnetic spectrum was discovered over a period of about 100 years. Here is a summary of some pivotal discoveries:

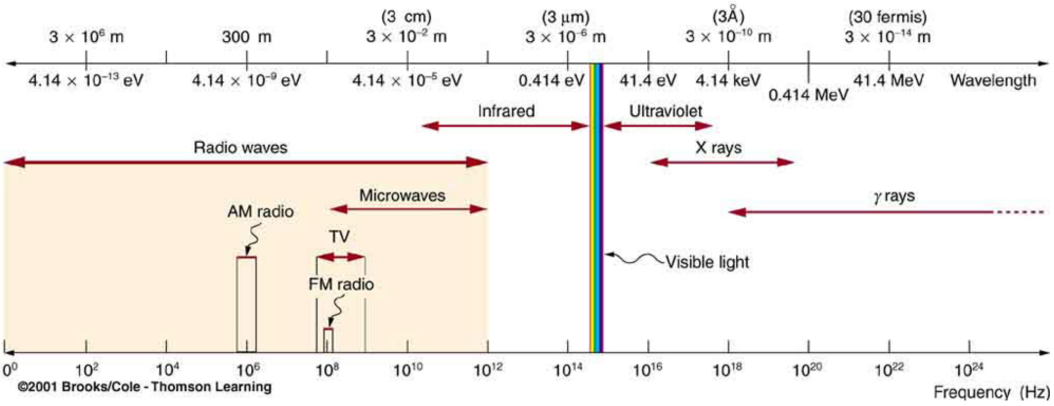

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Figure 7: Electromagnetic spectrum.

Infrared Radiation. Infrared radiation was discovered by the astronomer William Herschel in **1800**. He used a thermometer to measure how much different colors refracted through a prism heat up a thermometer bulb. To his surprise, when he place the thermometer beyond the visible red end of the spectrum, the thermometer still registered higher-than-normal temperatures. He deduced that there must be invisible "rays" present in the spectrum "beyond red." He had discovered the infrared part of the spectrum.

Ultraviolet Radiation. The ultraviolet spectrum was discovered in **1801**, a year after infrared radiation by the German physicist Johann Riter. Instead of using a thermometer, he made exposures on photographic plates and found that invisible rays had exposed the plate beyond the blue end of the spectrum.

Radio Waves. The German physicist Heinrich Hertz (whom the Hertz was named for) discovered radio waves in **1885**. He generated an electrical spark between two conducting spheres and discovered that a secondary spark was induced in a similar circuit some distance away. Hertz had made the first radio and antenna. The original spark generated an electromagnetic wave (a radio wave) that induced currents in the antenna to produce the secondary spark. This experimental discovery came 12 years after Maxwell theorized that light was an electromagnetic wave.

X-Rays. X-Rays were discovered in **1895** by Conrad Rontgen. Rontgen was working with Crookes tubes, which are partially-evacuated glass tubes containing a pair of electrodes. Crookes tubes were known to produce cathode rays (which were later shown to be electrons by J.J. Thomson in 1897) when a high voltage was placed across the electrodes. When the cathode rays strike the inside of the glass tube, they cause the glass to fluoresce and glow. When even higher voltages are applied (in excess of 5000 Volts), Rontgen noticed that a new kind of ray was produced that could pass through cardboard barriers and other objects and expose photographic film. He called these rays

"X-rays." To demonstrate his discovery, Rontgen famously passed the rays through his wife's hand to produce the first human X-ray (see Figure). Rontgen received the first Nobel Prize in physics in 1901 for the discovery of X-rays.

It wasn't until **1912** that Max von Laue showed that X-rays were a form of electromagnetic radiation. He shot X-rays though crystal lattices to produce diffraction patterns, demonstrating that X-rays are waves. This technique is now used to study crystalline structure from the X-ray diffraction pattern. Max von Laue received the 1914 Nobel Prize for the discovery of X-ray diffraction.

gamma rays. Gamma rays were discovered in experiments with radioactive elements by Paul Villard in **1900**. Ernest Rutherford coined the terms alpha, beta and gamma rays, ordering them in terms of increasing penetration into materials. They were shown to be a form of electromagnetic radiation in **1914** by their ability to be reflected from crystalline surfaces.

1.7 1873: Maxwell's Equations

In 1873, Scottish physicist James Maxwell published his seminal work on electromagnetism. His work unified electric and magnetic fields into an elegant set of equations now known as Maxwell's equations:

$$\begin{aligned}
\oint \vec{E}\cdot d\vec{A} &= \frac{1}{\epsilon_0} q_{enc} \\
\oint \vec{B}\cdot d\vec{A} &= 0 \\
\oint \vec{E}\cdot d\vec{s} &= -\frac{d\Phi_B}{dt} \\
\oint \vec{B}\cdot d\vec{s} &= \mu_0\epsilon_0 \frac{d\Phi_E}{dt} + \mu_o I_{enc}
\end{aligned}$$

He also showed that in free space, this set of equations simplifies to two independent wave equations, one for the electric field and one for the magnetic field. In one dimension, these equations are:

$$\frac{\partial^2 E}{\partial t^2} = \frac{1}{\mu_0\epsilon_0}\frac{\partial^2 E}{\partial x^2}$$
$$\frac{\partial^2 B}{\partial t^2} = \frac{1}{\mu_0\epsilon_0}\frac{\partial^2 B}{\partial x^2}.$$

The speeds of these waves are the same:

$$c = \frac{1}{\sqrt{\epsilon_0\mu_0}} \approx 2.9979 \times 19^8 \text{ m/s}.$$

Maxwell argued that the closeness of this speed to the speed of light was unlikely to be a coincidence. He correctly suggested that light is an electromagnetic wave. What remained to be understood, was what this calculated velocity was relative to. Thermodynamics predicts that sound waves travel at a given speed relative to the air or gas through which the waves travel. Fluid dynamics predicts the speed of surface waves relative to the water itself. The question remained: what is the speed of light relative to? At the time of Maxwell's work, the physics community widely believed that light must propagate through some medium, which they called the "ether." This ether must pervade the universe since light travels from distant stars to us.

1.8 1887: The Michelson-Morley Experiment

In 1887, Michelson and Morley designed an experiment to detect the ether. If the speed of light c is relative to an ether that pervades the universe, then they suggested that we might observe the speed of light to vary if we move relative to that ether. For example, if we travel in the same direction as a light wave, then the speed of the wave relative to us should be a bit less than if we were stationary with respect to the ether. If we let c be the velocity of light relative to the ether (in the $+x$ direction), and u be our velocity relative to the ether, the the speed of light relative to us should just be $c - u$. Similarly, if we travel in the opposite direction compared to a light wave, then the speed of the wave relative to us should be a bit more than if we were stationary with respect to the ether, or $c + u$. Michelson and Morley designed an experiment to measure the velocity of the Earth through the ether. They constructed an interferometer to accurately compare the velocity of light in different directions. However, to their surprise, they found no evidence that the velocity of a light beam depends on its angle relative to the motion of the earth through space to an accuracy of 5 km/s. (For comparison, the average velocity of the earth around the sun was known to be about 30 km/s and now we know the velocity of the sun around the center of the Milky Way is about 220 km/s.)

Michelson and Morley's result is often called the most famous negative result in physics. 19^{th} Century physicists were certain there *must* be an ether to support electromagnetic waves. If light waves didn't travel with respect to a medium, then what is the constant speed of light relative to?

1.9 1905: Einstein's Theory of Special Relativity

In 1905, Einstein suggested that light waves travel at a constant speed relative to *everyone* and *everything* in the universe. We all see the same speed of light independent of the velocity of the light source or the observer. Everyone sees the same speed. The constancy of the speed of light was one of Einstein's two fundamental postulates upon which he built his special theory of relativity, and directly leads to some of the most revolutionary predictions in physics.

1.10 1905: Einstein's Theory of the Photoelectric Effect

1905 was a good year for Einstein. He published three revolutionary papers, two of which lead to new understandings about light. Special relativity was one of the papers. The second paper was on the photoelectric effect. We will discuss the photoelectric effect later in the semester. But for now, we'll just say that Einstein interpreted this effect to argue that light must and (at least in some circumstances) like a particle! In 1926, an American chemist, Gilbert Lewis, named this particle a "photon." Einstein won the 1921 Nobel Prize for his theory of the photoelectric effect and the discovery of the photon.

1.11 Wave-Particle Duality

The fact that light sometimes acts like a wave and sometimes a particle appears to be a universal property of all quantum objects. Both massless light particles and massive material particles, such as protons and electrons, appear to exhibit wavelike properties in some situations. We will explore the wave-particle duality of both light and massive particles in the second half of this course.