EGR491 Notes: Optics, Part 1

Refs, some cited, some not:

1. https://cosmosmagazine.com/physics/what-is-light
2. http://www.canon.com/technology/s_labo/light/001/11.html
3. Fundamentals of Physics, Halliday and Resnick
4. Telescopes and Eyepieces Astrographs, Smith et al.
5. How to Make a Telescope, Texereau

Physical Optics

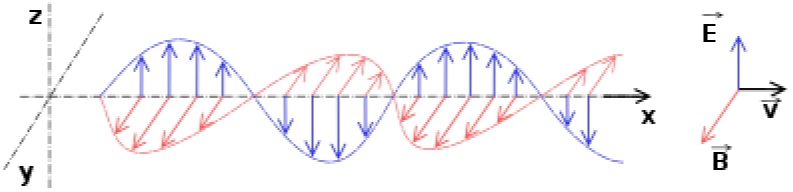
Explains the complex wave/particle nature of electromagnetic waves. It includes diffraction, polarization, interference, and atomic absorption/emission of light.

Electromagnetic Waves

What are electromagnetic waves? Reference [1] gives a good description:

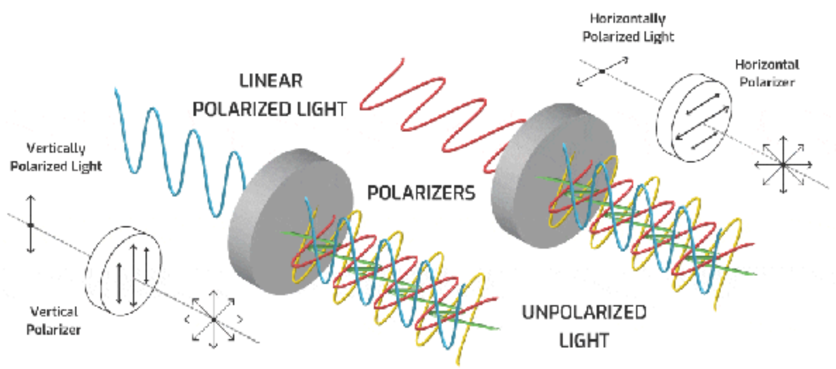
> We can trace the first steps towards understanding light's makeup to a benchtop in Copenhagen in 1820, where Danish scientist Hans Christian Ørsted was giving a lecture on electricity.
>
> A compass happened to be sitting near the battery he was using in his demonstration and he noticed the compass needle suddenly jerking when he switched the battery on or off. This meant electricity and magnetism were related – or, as it was more formally described later, a changing electric field creates a magnetic field.
>
> Then 11 years later, English scientist Michael Faraday discovered the opposite rang true: that a changing magnetic field also creates an electric field.
>
> It was the Scottish physicist James Clerk Maxwell who collected these ideas about electricity and magnetism (plus a few others) and pulled them together into one coherent theory of "electromagnetism".
>
> But Maxwell's most celebrated insight was when he combined the work of Ørsted and Faraday to explain the essence of light.
>
> He realized that a changing electric field could create a changing magnetic field, which would then create another electric field and so on. The result would be a self-sustaining electromagnetic field, endlessly repeating, travelling incredibly fast.
>
> How fast? Maxwell was able to calculate this too, at about 300,000,000 metres each second – pretty close to what had recently been measured for the speed of light.
>
> **And so this is what light is: an electric field tied up with a magnetic field, flying through space.**

Electromagnetic waves (from Wikipedia):



Electromagnetic waves, making up electromagnetic radiation, can be imagined as self-propagating transverse oscillating waves of electric and magnetic fields. This diagram shows a linearly polarized, plane EM-wave propagating from left to right (along X-axis, in left-handed coordinates). The electric field is in a vertical plane (X/Z axes) and the magnetic field in a horizontal plane (X/Y axis). The electric and magnetic fields in polarized EM waves are always in phase and in planes at 90 degrees to each other. (Note: **this image shows polarized light**).

Polarization:
"Electromagnetic waves are transvers waves with alternating electric and magnetic field vectors being at right angles to the direction of propagation" (Halliday). When all but one direction of the transverse wave is eliminated, the light is said to be polarized:



Direction of travel

(light is traveling from bottom right to upper left)

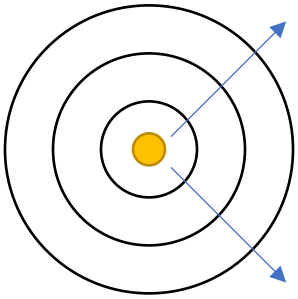
If horizontal and vertical polarizers are placed in the path of light, virtually all of the light will be blocked. When light from the sun strikes a road or other surface, the reflected light is highly polarized. Polaroid sunglasses are common polarizers, and are oriented to effectively block the polarized light; removing road "glare" from your vision. If you turn the glasses 90 degrees, the polarizing axis of the glasses become aligned with the polarizing direction of the reflected light and the glare returns.

Natural engineering: if humans can design something useful based on polarized light, I bet nature has too: https://www.aaas.org/blog/qualia/cuttlefish-eyes-see-polarized-light

In astronomy, polarizing plates are used to reduce the brightness of incoming light; regardless of frequency (hence, they are referred to as "neutral density filters"). The moon is very bright, and neutral density filters are commonly used when viewing the moon. If two polarizing plates are used, the amount of light transmission can be adjusted by the user.

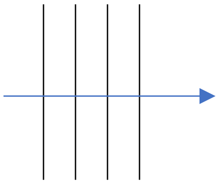
Wave Optics

Light travels radially, in 3-dimensions, away from a point source; like ripples in a pond when a pebble is dropped in the water. Since it is 3-dimensional, the energy is dispersed cubically with distance. Double the distance, and the amount of light energy traveling through a given area diminishes by 2^3 (it is 1/8th the energy per unit area).



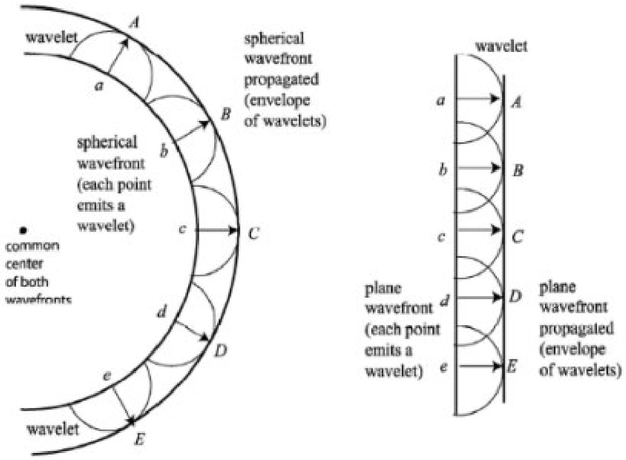
Light traveling away for the point source.

If we are a great distance from a point source, the wave front becomes a flat surface traveling in a single direction:



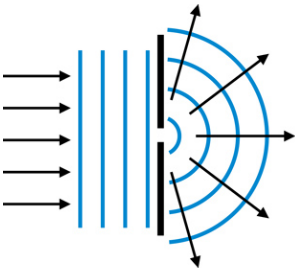
Huygens' Principle

Christian Huygens (Dutch physicist, ca. 1678) proposed a wave theory for light. Huygens' principle states: *All points on a wave front can be considered as points sources for the production of spherical secondary wavelets. After time t the new position of the wave front will be the surface of tangency to these secondary wavelets*.

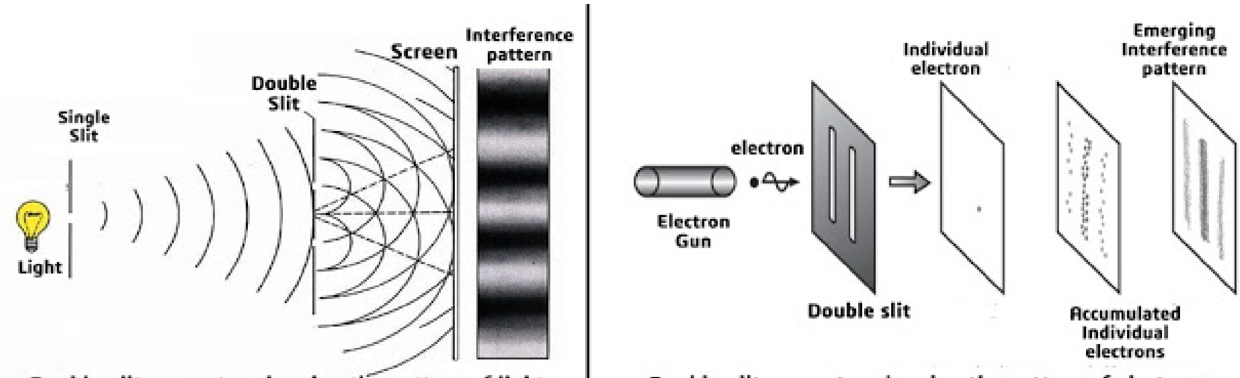


https://selfstudypoint.in/huygens-principle/

If we have a straight wave front (as shown in the right side of the image above) and place a small slotted opening (an opening equivalent to the wave length) in its way, it will pass through the slot and emerge as a point source. Diffraction allows waves to “bend” around corners.



If we put a second slot, we effectively create two point sources – creating the famous “double slit experiment” which demonstrates the constructive and destructive interference pattern created by propagating waves. If wave were a particle, there would be 2 bright spots behind the slit – each corresponding to the location of the opening. But that is not what happens. The double slit will create areas of brightness (where the wave peaks meet) and areas of darkness (where the peak of one wave meets the trough of the other – “canceling out” the light):



Double-slit apparatus showing the pattern of light

Double-slit apparatus showing the pattern of electron

https://spl-binal.blogspot.com/search/label/Double-slit%20experiment

Implications in Telescope Design:
Diffraction effects are noticed in two significant ways in telescopes – you may have noticed both of these in photographs. Let’s take them one at a time.

All stars (except Sol, aka the Sun) are so far away, that they are effectively point sources of light – they should have infinitesimal size. Yet, if you go out at night and look at the stars, while dim stars do appear to be quite small, almost points, bright stars appear to be clearly bigger than a point. This is the result of diffraction in your eye. The effect shows up in photographs as well. Looking at the photo below, you can identify the brighter stars even though the amount of light leaving the paper is not more intense.

The brighter stars are bigger in this photograph – the paper does not emit more intense light from them.

Why? The *Airy disk* is the answer (Wikipedia):

> The diffraction pattern resulting from a uniformly-illuminated circular aperture has a bright region in the center, known as the Airy disk, which together with the series of concentric bright rings around is called the Airy pattern. Both are named after George Biddell Airy. The disk and rings phenomenon had been known prior to Airy; John Herschel described the appearance of a bright star seen through a telescope under high magnification for an 1828 article on light for the Encyclopedia Metropolitana:
>
> ...the star is then seen (in favourable circumstances of tranquil atmosphere, uniform temperature, etc.) as a perfectly round, well-defined planetary disc, surrounded by two, three, or more alternately dark and bright rings, which, if examined attentively, are seen to be slightly coloured at their borders. They succeed each other nearly at equal intervals round the central disc...

As a result, the "point" of light is spread out over a finite area, consisting of a bright area in the middle, and secondary, much less bright, rings. The brighter the light, the more noticeable the distribution:

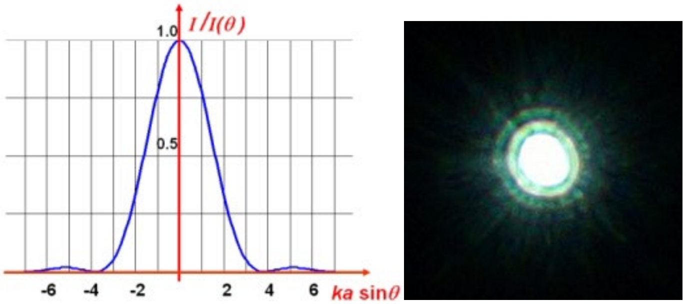
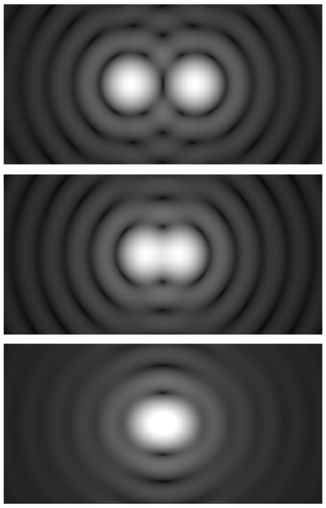


Image at left: graphical display of light intensity distribution. Image at right: Airy disk captured by 2000 mm camera lens at f/25 aperture. Image size: 1×1 mm. (Wikipedia).

The size of the Airy disk is proportional to the wave length of light and inversely proportional to the aperture size (the size of the objective lens or mirror in a telescope) – bigger optics reduce the size of the disk. (Shorter wave lengths also reduce the size of the disk, but astronomers have no control over that). The size of the disk determines the resolution of the telescope (or microscope). The image below shows what happens as two point source of light become closer together; they begin to merge together and appear to be a single source (Wikipedia):



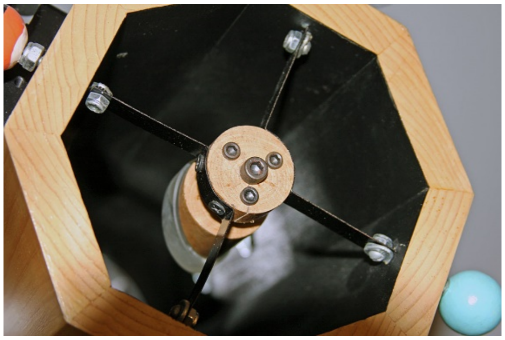
Binary stars are two stars that orbit each other, and therefore, are very close together. Many of these are easily resolved even in small amateur telescopes, but others are difficult to resolve. Larger telescopes are better able to resolve the individual stars.

A note about resolution and size of optics. Resolution improves with larger optics – but the optics do not need to be a continuum. In other words, if we can "link" different optical detectors (telescopes) together, the spacing between the optics is the effective size. Two telescopes placed on opposite sides of earth would have an effective diameter of the earth; that could have very high resolution. This is common in large radio telescope arrays, and a few optical telescopes as well.

The VLA (Very Large Array) radio telescope in New Mexico used *https://public.nrao.edu/*

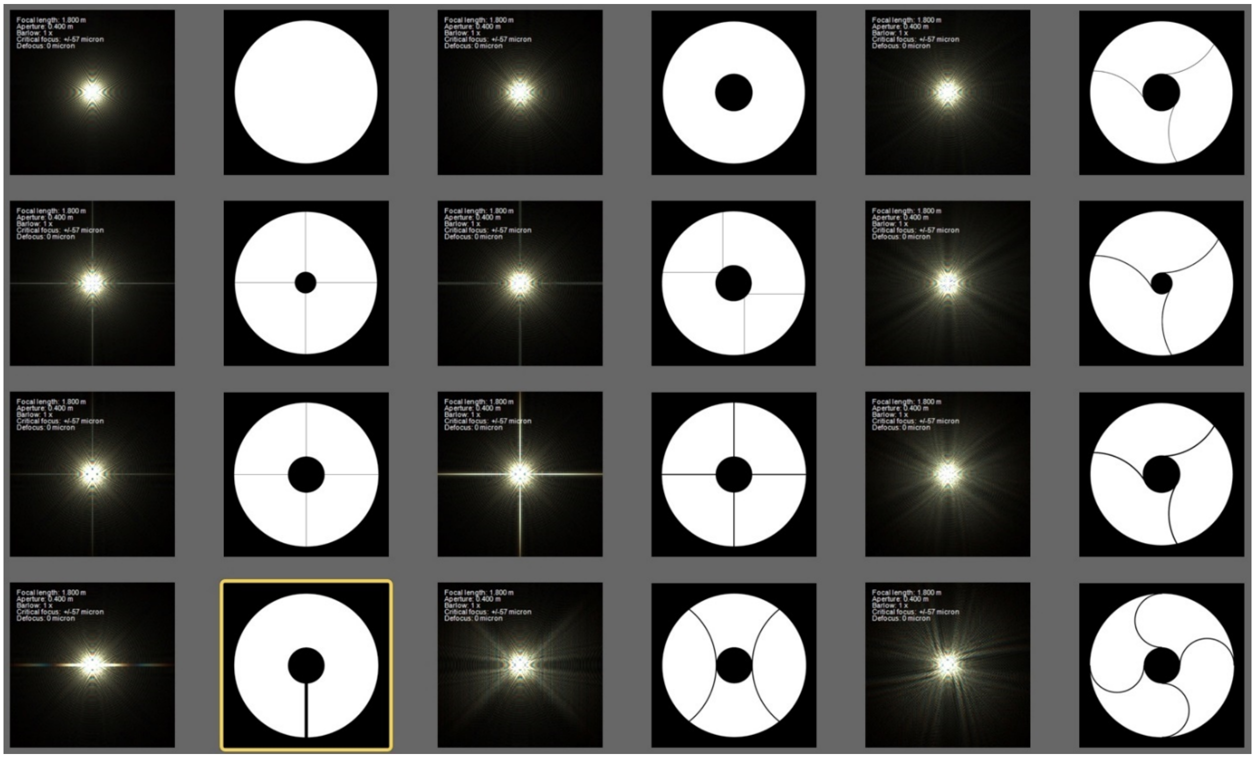
The other diffraction effect is not noticed with the unaided eye, but is visible through certain telescopes and recorded faithfully in photographs. Did you ever notice that in some photographs, stars of “spikes” emanating from them – as do stars shown here:

These are called diffraction spikes, and they are the result of thin linear obstructions within certain telescopes. These obstructions are structural components to “Newtonian” telescopes: they support a secondary mirror. The following image shows the end of a Newtonian telescope (the end that the light enters):



Structural elements hold the secondary mirror in the center of the light-path. This is referred to as the “spider”.

Various spider designs result in different diffraction patterns; including patterns that do not produce spikes (they ‘smear’ the diffraction effect)



https://www.cloudynights.com/topic/495707-spider-and-secondary-diffraction-what-to-do-what-to-avoid/

Light acts as particle and as a wave – both, depending upon how it is observed.

From Ref [2]: What Is a Photon?

> The light particle conceived by Einstein is called a photon. The main point of his light quantum theory is the idea that light's energy is related to its oscillation frequency (known as frequency in the case of radio waves). Oscillation frequency is equal to the speed of light divided by its wavelength. Photons have energy equal to their oscillation frequency times Planck's constant. Einstein speculated that when electrons within matter collide with photons, the former takes the latter's energy and flies out, and that the higher the oscillation frequency of the photons that strike, the greater the electron energy that will come flying out. In short, he was saying that light is a flow of photons, the energy of these photons is the height of their oscillation frequency, and the intensity of the light is the quantity of its photons.

Bottom line implication: high frequency (short wave length) electromagnetic waves have greater energy than low frequency waves.