Lab 10: Exploring the Multiwavelength Universe

1 Introduction: Let There Be Light

At its core, observational astronomy is the art of collecting light. All luminous matter in the Universe emits light in some shape or form. As astronomers, it's our job to capture and interpret this light.

While some light can be effectively processed by the naked eye (we call this "visible" or "optical" light), the majority of light in the Universe is imperceptible to humans. Electromagnetic radiation (just a fancy, science-y term for light) spans a broad *spectrum* of flavors, from low-frequency radio waves to high-energy gamma rays (see Figure 2). Astronomical objects emit electromagnetic radiation across the entire spectrum; therefore, in order to fully understand the Universe, we must be able to observe all varieties of light. While we as humans cannot *see* microwaves or radio waves or X-rays, we are more than capable of building special detectors that can. Collectively, we refer to these detectors as "telescopes."

2 The Anatomy of a Light Wave

Light can be thought of as either a *wave* (often referred to as an "electromagnetic" wave) or as a *particle* (called a "photon"). While both descriptions of light are perfectly valid, we'll primarily be focusing on the wave nature of light in this lab. When physicists refer to "waves," they're referring to steady, propagating wiggles (or, in technical terms, "oscillations"), like those illustrated in Figure 1. These waves are comprised of a series of alternating *peaks* (high points) and *troughs* (low points); we can therefore characterize a wave by measuring its *amplitude* (half the vertical distance from the bottom of a trough to the top of a peak) and its ***wavelength*** (the horizontal distance from peak to peak or from trough to trough). For a light wave, the amplitude tells us how bright (or *intense*) the light is. Meanwhile, the wavelength controls the "identity" of a light wave – the wavelength dictates what color the light will be, how much energy is carried by the light, how deeply the light can penetrate into matter, and more. The wavelength is the key property that we'll be exploring in today's lab.

Figure 1 shows only the wavelength range of "visible" light – the light that we, as humans, can see with our naked eyes. Importantly, however, light can exist at wavelengths far longer and far shorter than the visible range, filling out the entire ***electromagnetic (EM) spectrum*** (Figure 2). At the longest wavelengths, we have *radio waves*; as we decrease the wavelength, we move through *microwaves*, *infrared light*, *visible light*, *ultraviolet light*, *X-rays*, and *gamma rays.* The wide variety of light that shines throughout the Universe makes observational astronomy an extremely rich field of study.

1. The electromagnetic spectrum is not just relevant in astronomy – we experience almost all wavelengths of the spectrum in our daily lives. For each region of the EM spectrum (radio, microwave, IR, visible, UV, X-ray, gamma), list one or two sources of that type of light that

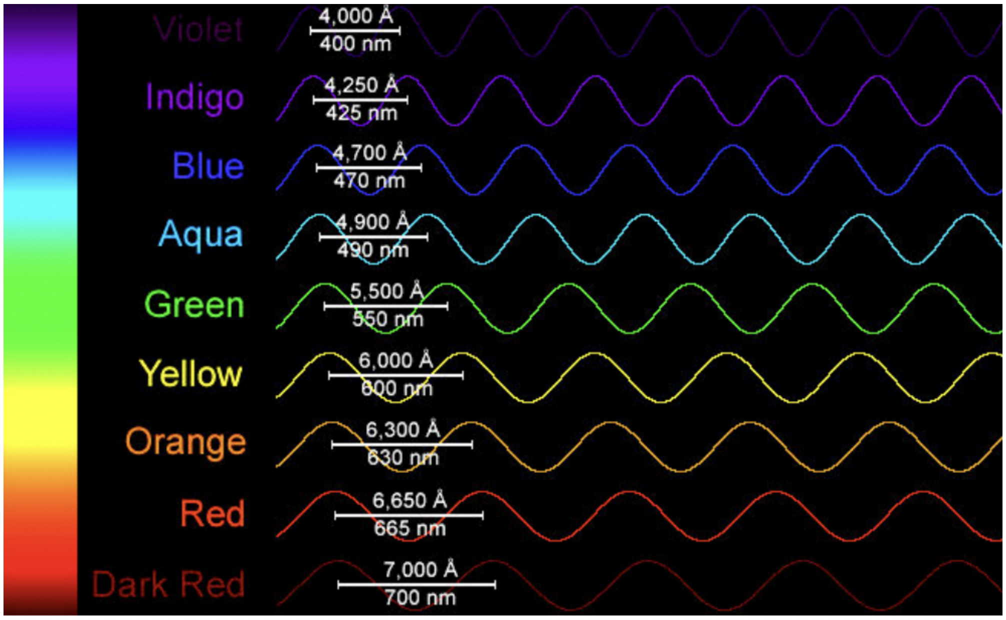

Figure 1: A collection of light waves with varying *wavelengths*. The wavelengths are reported both in units of nanometers (nm, 10^{-9} meters) and in units of angstroms (Å, 10^{-10} meters).

we may find on Earth. (*Hint*: this website has some fun examples: `https://imagine.gsfc.nasa.gov/science/toolbox/emspectrum1.html`)

2. The average human body cell is 100 μm in diameter. Compare this to the typical wavelength of a radio wave and to the typical wavelength of a gamma ray. Why do you think gamma rays are harmful to humans but radio waves are not?

3. At roughly what wavelength do you think the Sun emits most of its light? (*Hint*: human eyes evolved to detect sunlight)

4. Different wavelengths of light have different *optical properties*, meaning that they behave differently when sent through a prism or lens or when bounced off a mirror. Navigate to `https://javalab.org/en/electromagnetic_waves_around_of_visible_rays_en/`. In the applet window, you can click and drag the mouse up and down to vary the wavelength of light passing through the prism.

   (a) Light is "bent" as it travels through a prism. As you vary the wavelength from long wavelengths to short wavelengths, how does the degree of bending vary? Are shorter

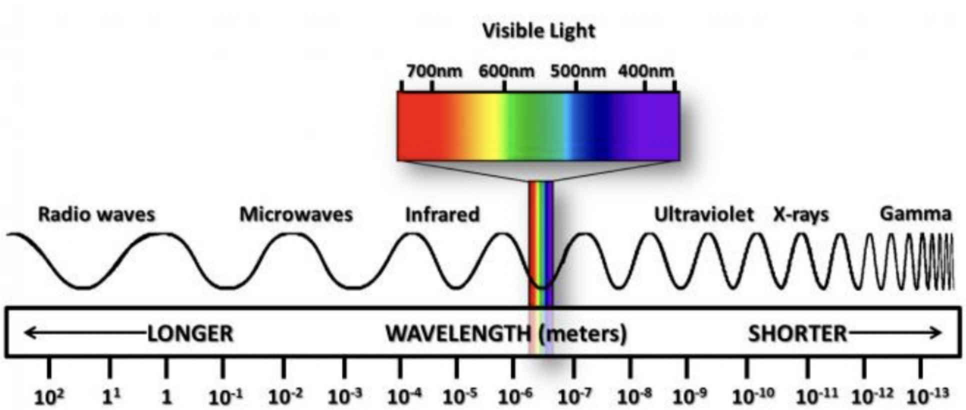

Figure 2: The electromagnetic spectrum: the broad assortment of light that permeates the Universe.

wavelengths bent more than longer wavelengths, or vice versa?

(b) This simulation only shows a *single* wavelength of light passing through the prism at any given time. If we instead sent "white light" (an equal mixture of all wavelengths) through the prism, what do you expect the light pattern emerging from the prism to look like?

3 The Multiwavelength Universe

The night sky shines in all wavelengths of the electromagnetic spectrum. Navigate to `https://www.nao.ac.jp/study/multiwave/en/`; we'll be using this site for the next few sections of this lab. Once the site loads, click the "start" button in the middle of the screen. The landing page shows the electromagnetic spectrum at the bottom of the screen, with each region labeled. Clicking on any of these labels will show you an image of the Antennae Galaxies composed of light from that particular region of the spectrum (with the exception of gamma rays, for which an image of the Antennae Galaxies is not shown). Moreover, once you've clicked on a specific wavelength range, you can scroll up or down (or use the dots on the right side of the screen) to learn more about the astronomical objects and phenomena that emit this light.

1. For three regions of the electromagnetic spectrum, briefly describe what we can learn about the Antennae Galaxies by observing in this wavelength range. Additionally, briefly describe

Figure 3: The James Webb Space Telescope (JWST) in all its glory.

two astrophysical phenomena that emit this type of light.

4 Why do we need so many telescopes?

No single telescope can observe the entire electromagnetic spectrum – if we wish to obtain consistently high-quality images of the Universe at multiple wavelengths, we need to design special detectors that are fine-tuned to receive light within relatively narrow wavelength ranges. For instance, radio telescopes typically have extremely large receivers in order to accommodate for the long wavelengths of radio light – but, if we were to try to observe the tiny wavelengths of X-rays or gamma rays with a radio telescope, we'd barely register a detection. Similarly, if we tried to observe visible light with the narrow aperture of an X-ray telescope, we'd get a very fuzzy, saturated image.

Let's take a closer look at a few telescopes. Navigate back to `https://www.nao.ac.jp/study/multiwave/en/`. Now, click on the tab at the bottom of the screen that says "Wavelength Guide" – this'll bring up a list of telescopes organized by wavelength range. Use this page (as well as the "Wavelengths and Targets" tab, located at the bottom of the screen) to answer the following questions.

1. The **James Webb Space Telescope** (JWST, see Figure 3) was launched into space in 2021. Find JWST on the "Wavelengths and Telescopes" chart.

(a) Which regions of the electromagnetic spectrum is JWST tuned to detect? What type of light will JWST primarily be observing?

(b) Many news outlets have stated that JWST will "replace" the Hubble Space Telescope. Looking at the "Wavelengths and Telescopes" chart, explain why this statement is not fully accurate. What telescope would it make more sense to label as the "predecessor" to JWST?

(c) Take a quick look at this JWST fact sheet: `https://jwst.nasa.gov/content/webbLaunch/assets/documents/WebbFactSheet.pdf`. Briefly describe two science cases that JWST will be focusing on.

2. The Atacama Large Millimeter/submillimeter Array – or *ALMA* – is an array of telescopes in Chile. Locate ALMA on the "Wavelengths and Telescopes" page. In which region of the electromagnetic spectrum does ALMA observe? List one type of astronomical object that ALMA can see well and very briefly describe this object.

3. You've heard some cool things about hot stars (pun intended). In what region of the electromagnetic spectrum do high-mass, high-temperature stars emit most of their light? Which telescopes would be best suited for observing these stars?

5 The Earth's atmosphere: Astronomy's greatest enemy

Light propagates perfectly fine through vacuum (the complete absence of matter), but as soon as we introduce matter – like the gas in the Earth's atmosphere – we run into trouble. As light passes through our atmosphere, gas scatters and deflects this light, affecting the clarity of ground-based telescope observations. Moreover, certain molecules in our atmosphere – like water, carbon dioxide, and ozone – can *absorb* incoming light, completely preventing some wavelengths from reaching the ground.

Let's explore the effects of the Earth's atmosphere in a bit more depth. First, navigate back to `https://www.nao.ac.jp/study/multiwave/en/`. Go back to the "Wavelength Guide" page (located at the bottom of the screen), and now click on the "Wavelength and Atmospheric Penetration" tab. This page should display a graphic illustrating how far different wavelengths of light can travel through our atmosphere. Using this diagram, answer the following questions.

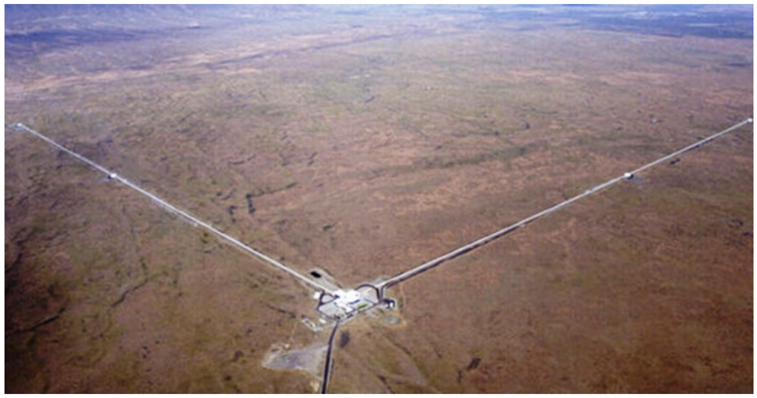

Figure 4: The Laser Interferometer Gravitational-Wave Observatory, or LIGO.

1. In which wavelength ranges can light reach the surface of the Earth (i.e., an altitude of 0 km)? Referring back to the "Wavelengths and Telescopes" tab, what are some *ground-based* telescopes that observe in these wavelength ranges?

2. Which wavelengths are affected the most by the atmosphere? Referring back to the "Wavelengths and Telescopes" tab, what are some telescopes that observe at these wavelengths?

3. Many ground-based telescopes, like the Subaru Telescope and the Keck Observatory, are built on the summits of very tall mountains. Why is the top of a mountain an optimal location for a telescope? (*Hint*: think about the air quality on top of a mountain vs. the air quality at lower altitudes)

4. Many ground-based telescopes, like ALMA and ACT, are built within extremely dry deserts. Why is a desert an optimal location for a telescope? (*Hint*: think about the air quality in a desert vs. the air quality in a moister environment)

6 Going beyond the Electromagnetic Spectrum

At the start of this lab, I said that observational astronomy was "the art of collecting light." This is 95% true. Let's take a little time to explore that other 5%. **Complete two of the three following questions.**

1. Read a little about **dark matter** at `https://www.space.com/20930-dark-matter.html`
   (a) In which region of the electromagnetic spectrum does dark matter radiate? Why does it make sense to describe dark matter as "dark"?

   (b) What percentage of all the matter in the Universe is attributed to dark matter?

2. When a charged particle is jiggled around, it produces an electromagnetic wave – that is, a jiggling charged particle produces radiation (which we've looked at extensively in this lab). It turns out that this applies to all matter: when a chunk of matter is jiggled around, it produces **gravitational waves**, or *gravitational radiation*. Read a little about gravitational waves and the gravitational wave "telescope" LIGO (Figure 4) at `https://www.ligo.caltech.edu/page/gravitational-waves` and `https://www.ligo.caltech.edu/page/what-is-ligo`.
   (a) What types of objects produce detectable gravitational waves?

   (b) What astrophysical information can we get from gravitational waves that we can't get from electromagnetic waves?

3. **Neutrinos** are very *very* tiny particles that move at speeds close to the speed of light. Read a little about the neutrino observatory *IceCube* at `https://icecube.wisc.edu/about-us/faq/`, at `https://icecube.wisc.edu/about-us/facts/`, or at `https://icecube.wisc.edu/science/research/`.
   (a) Where is IceCube located, and why?

   (b) What astrophysical information can we get from neutrino detections that we can't get from light observations?

7 Conclusions

1. With the coming decades promising rapid advancements in telescopes, detectors, and observatories of all types, the pursuit of **"multi-messenger"** astronomy – the combination of observations from electromagnetic radiation, gravitational waves, neutrinos, and cosmic rays

to achieve a common scientific goal – is quickly reaching maturity. Based on what we've covered in this lab, why do you think multi-messenger astronomy is important? Give one example of a discovery will we be able to make with multi-messenger observations that we couldn't have made with just observations of light.

2. What did you like or dislike about this lab?

3. Write down at least one question that you still have after finishing this lab.