

The Cosmic Microwave Background

(The Oldest Light in the Universe!)

Learning Goal: Explain that an expanding universe would cause ancient light to become redshifted, and cite this light as evidence for the Big Bang model.

Curricular Alignment to NGSS

Science and Engineering Practices

1. Asking questions (for science) and defining problems (for engineering)
2. Developing and using models
3. Planning and carrying out investigations
4. Analyzing and interpreting data
5. Using mathematics and computational thinking
6. Constructing explanations (for science) and designing solutions (for engineering)
7. Engaging in argument from evidence
8. Obtaining, evaluating, and communicating information

Crosscutting Concepts

1. Patterns
2. Cause and effect
3. Scale, proportion, and quantity
4. Systems and system models
5. Energy and matter
6. Structure and function
7. Stability and change

NGSS content-specific standards

HS-ESS1-2 Earth's Place in the Universe - Construct an explanation of the Big Bang theory based on astronomical evidence of light spectra, motion of distant galaxies, and composition of matter in the universe.

PS4.A: Wave Properties

The wavelength and frequency of a wave are related to one another by the speed of travel of the wave, which depends on the type of wave and the medium through which it is passing. (HS-PS4-1)

PS4.B: Electromagnetic Radiation

Electromagnetic radiation (e.g., radio, microwaves, light) can be modeled as a wave of changing electric and magnetic fields or as particles called photons. The wave model is useful for explaining many features of electromagnetic radiation, and the particle model explains other features. (HS-PS4-3)

When light or longer wavelength electromagnetic radiation is absorbed in matter, it is generally converted into thermal energy (heat). Shorter wavelength electromagnetic radiation (ultraviolet, X-rays, gamma rays) can ionize atoms and cause damage to living cells. (HS-PS4-4)

PS4.C: Information Technologies and Instrumentation

Multiple technologies based on the understanding of waves and their interactions with matter are part of everyday experiences in the modern world (e.g., medical imaging, communications, scanners) and in scientific research. They are essential tools for producing, transmitting, and capturing signals and for storing and interpreting the information contained in them. (HS-PS4-5)

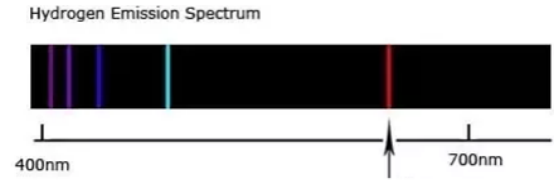
Notes to Teachers:

- The first section called Review is mostly intended to help teachers understand where this activity fits into the scope and sequence of the unit, so you might prefer not to give that part to your students. In the student version, there is only the pre-lab questions and no written review.
- This activity is designed to be used after the spectroscopy activities, specifically the “Spectroscopy of Hot Objects” activity, because it is there that they make connections between an object’s temperature and the colors of light it emits. Furthermore, students should already understand that the universe is expanding, and that this expansion causes redshift of distant light. These two ideas are key to understanding why the cosmic microwave background is evidence for the Big Bang.
- The concepts of expanding and contracting gases are intended to be **analogies** only, to help students think about how the universe would cool off as it expands, but this is not a literal model used by physicists. More correct explanations would require math and physics skills above even an undergraduate level.

Review

1. Hot things glow!

In a previous class, you looked at a tube filled with hydrogen gas, and when the tube was turned on it glowed a pinkish-red color. When you looked at the tube with a handheld spectroscope, it looked like this:

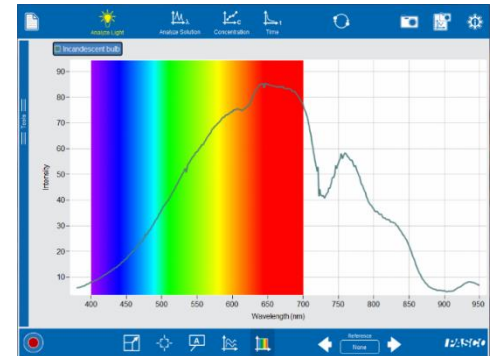


Above: Hydrogen Emission Spectrum.
Source: quora.com

This is a good reminder that objects like hydrogen gas will glow brightly when they get hot. It's also a reminder that hydrogen is very abundant in the universe, because we see this emission spectrum everywhere we look in space.

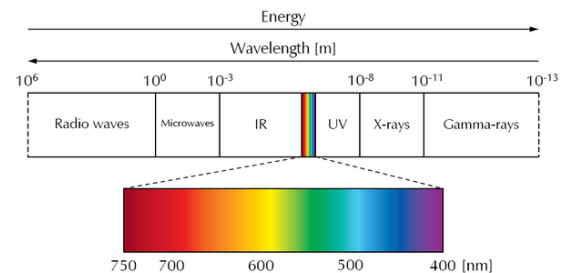
You may have also had a chance to see what happens when you put an old-fashioned (filament-type) light bulb in front of a spectrometer. The spectrum looks something like this:

One thing that's interesting about this spectrum is that some of the light produced by the bulb cannot be seen by the human eye – it is infrared light, which has a longer wavelength than visible light. So here is another example of something hot producing light, but instead of just a few colors like the hydrogen tube, it produces a wide range of colors.



Above: Incandescent Light Bulb Spectrum.
Source: pasco.com

Many things in the universe, especially stars, have this same behavior – think of the rainbow produced by sunlight after a storm, where the rainbow shows the full range of visible sunlight colors. And they don't just produce light in the infrared and visible parts of the EM spectrum; some stars emit ultraviolet light and radio waves, and some special objects like black holes and neutron stars even emit X-rays and gamma rays!



Above: The Electromagnetic Spectrum.
Source: nist.gov

2. Pressure and Temperature

The Hubble Law says that the universe is expanding, based on evidence that almost all the galaxies surrounding us are moving away (they are redshifted). Since most of the universe is made of hydrogen gas, it's important to understand what happens when a gas expands.

With a demonstration like the "fire syringe," you saw that when a gas such as air is compressed, it gets extremely hot as long as the air is not able to cool off by its surroundings. (example: [Veritasium's](https://www.youtube.com/watch?v=4qe1Ueifekg) channel on YouTube <https://www.youtube.com/watch?v=4qe1Ueifekg>)

The reverse is also true: when you force a gas to expand, it will get colder!

Summary

- The universe is mostly hydrogen gas.
- The universe is expanding.
- When a gas expands it cools, and when it compresses it gets hotter.

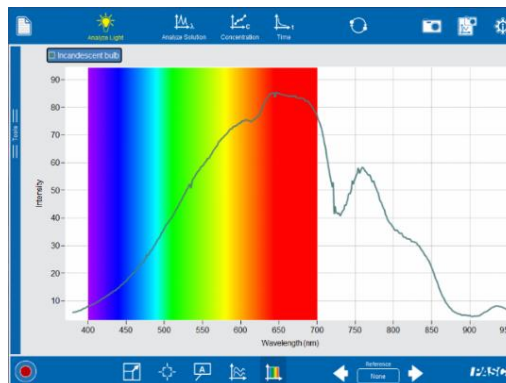
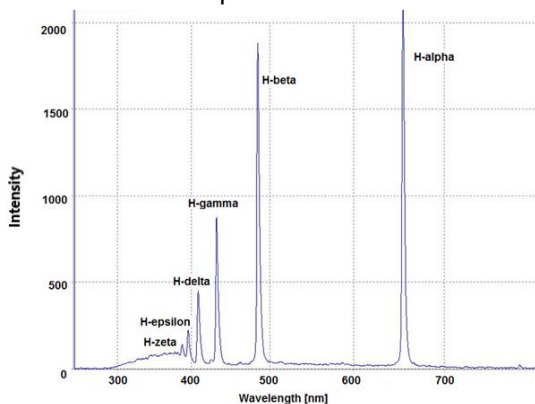
Based on this information, what do you think the universe might have been like, a long time before the present day? Write a brief description below describing the pressure and temperature.

Answers to Prelab questions

1. In a previous class, you did some experiments with spectroscopy. What can you learn about an object by using spectroscopy?

Answer: Many things can be learned. For example, you can tell how fast the object is moving if the spectrum is redshifted or blueshifted, and you can tell the object is far away if the intensity is lower. You can also determine identity and composition based on features like emission lines and absorption lines.

2. Examine the two spectra below.



- a. Which spectrum is most likely the spectrum for a hot gas, and how do you know?

Answer: The spectrum on the left shows only emission lines so it's the spectrum of a hot gas.

- b. Which spectrum corresponds to a hot metal such as a light bulb filament, and how do you know?

Answer: Hot metals give off a wide range of light, so the spectrum on the right is correct.

3. So far you have mostly seen spectra that use the visible part of the electromagnetic spectrum. What are the other categories of electromagnetic radiation besides visible? You should be able to list at least 5.

Answer: Gamma, X-ray, Ultraviolet, Infrared, Microwave, Radio

4. Your instructor may show you a demonstration using a device called a “fire syringe.” What happens to the gas inside a fire syringe when it gets compressed? (alternative: watch this fire syringe video: <https://www.youtube.com/watch?v=4qe1Ueifekg>)

Answer: When the gas is compressed it gets hot, hot enough to set the cotton on fire.

Note to teacher: we avoid contrasting adiabatic/isothermal processes here, but a clever student might point out that if the compression happened slowly enough there'd be no temperature increase.

5. Think about the opposite situation to the fire syringe. What would you expect to happen to a gas if it is forced to expand?

Answer: When a gas is forced to expand it will cool off.

Note to teacher: this again assumes an adiabatic expansion. In the case of the fire syringe the process is quick enough to be modeled as adiabatic; in the case of the 14 billion year expansion of the universe, one might argue that the process is only adiabatic if the universe doesn't exchange thermal energy with its "surroundings!"

6. In another lesson, you learned about the relationship between how far away a galaxy is and the colors of light it emits. This relationship is sometimes called Hubble's Law. What does this relationship tell us about the universe?

Answer: The further away a galaxy is, the more it is redshifted, meaning the faster it is moving away from us. This gives evidence that the universe is expanding.

7. Based on all the questions you answered previously, what would most likely be true about the early universe? (*hint: if the modern universe is very large and filled with cold gas now, what would have been true much earlier?*)

Answer: The universe today is filled with cold gas, mostly hydrogen and helium. The early universe would have been more compact and hotter. If everything is expanding and cooling now, the early universe must have been smaller, hot and dense.

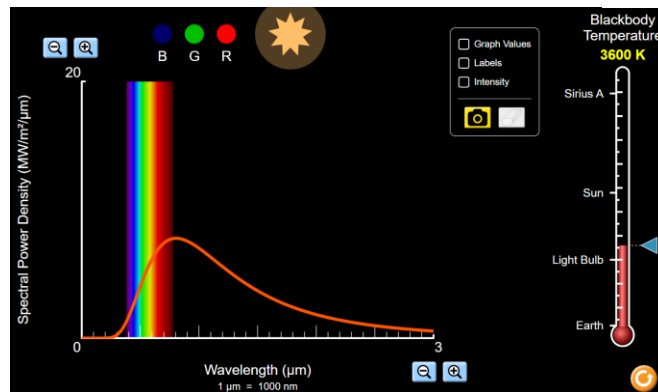
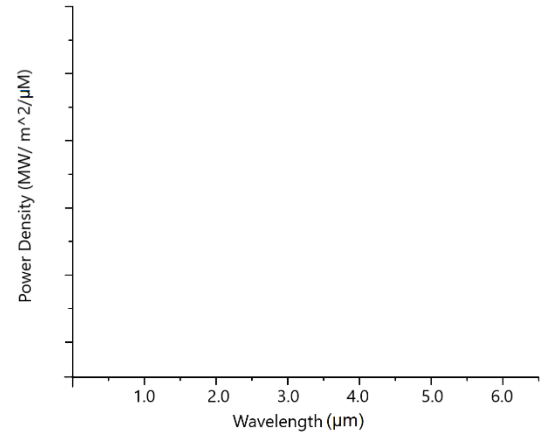
Explain– The Cosmic Background

- Based on what you’ve learned so far, you know that the early universe was a hot and dense environment, and it would be emitting light whose wavelength depends on its temperature. Suppose that 13 billion years ago, the average temperature of the universe was 3600 degrees Kelvin. **Note to teacher: students may complain that this 3600K number seems arbitrary or pulled out of nowhere. The key idea is that the hot dense universe would have stopped emitting light once it cooled off enough for hydrogen to form. This can be calculated to be 3000-4000K.**

- What would you expect the **peak** wavelength to be for the light being emitted by the early universe?

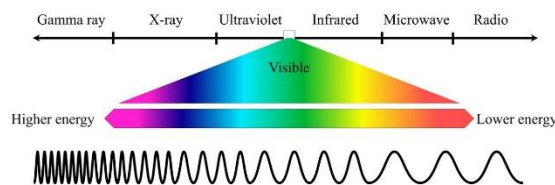
Answer: Approximately 1 μm .

- On the graph at right, sketch a curve to represent the type of light you would expect to measure. (notice the graph has the same axes as the graph from the blackbody simulation, so you can use that simulation for help.)



- What category of light would this be? Circle one.

Electromagnetic Spectrum



Answer: This would be mostly infrared light.

- Think back to what you learned about Hubble’s Law. How was the **redshift** of galaxies used to demonstrate the universe expansion?

Answer: Because the universe is expanding, the light from galaxies is redshifted because all of the galaxies (outside our local neighborhood) are moving away from us.

3. Rebecca Smethurst (AKA “Dr. Becky”) is a [popular astrophysicist](#) on YouTube. In one of her videos, she said the easiest way to travel back in time is to walk outside at night and look up. What do you think she meant by this?

Answer: All of the light we see in the night sky is old, because it takes time for the light to reach us. For nearby stars the light is a few years old, for nebulas the light is a few thousand years old, and you can even see light from galaxies that is millions of years old. Even on nights where the Moon is visible, the light takes 8 minutes to reach the Moon from the Sun, and another 1.5 seconds to reach the Earth from the Moon!

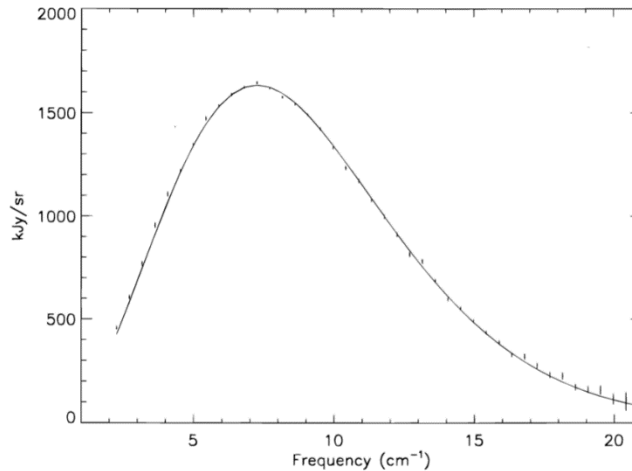
4. If the early universe 13 billion years ago was emitting mostly infrared light, it would still be present in today’s universe. However, this light would be affected by the constant expansion of the universe during that time.

What would you expect to happen to the peak wavelength of this light due to the universe expansion?

Answer: In a similar way to how the light from moving galaxies is redshifted, the infrared light from the early universe is also redshifted. Because the light is over 13.5 billion years old, the redshift is very dramatic. So the peak wavelength of the light would be much longer than $1\mu\text{m}$.

Evaluate

- A. The graph in the figure below comes from a famous article in the 1996 *Astrophysical Journal* using a microwave telescope called COBE (and an instrument called FIRAS) that was pointed at the entire night sky. The FIRAS instrument produced a curve based on all the wavelengths of light it detected over the entire sky.

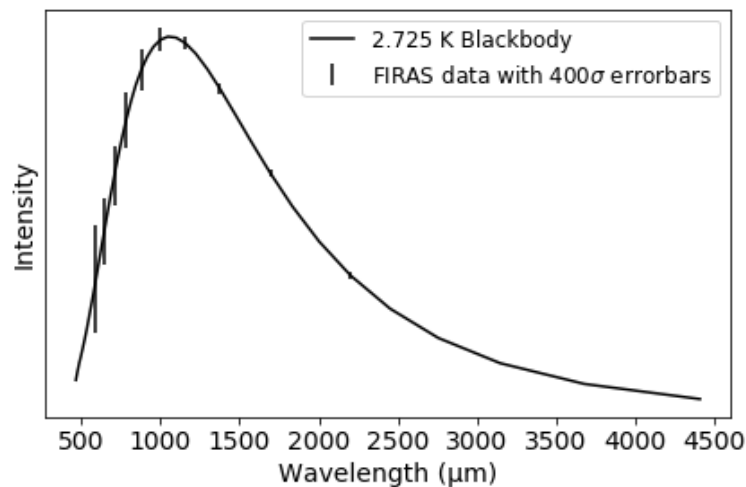


Above: *The Cosmic Microwave Background, measured by COBE.*

Note: the x-axis is frequency.

Source: nasa.gov

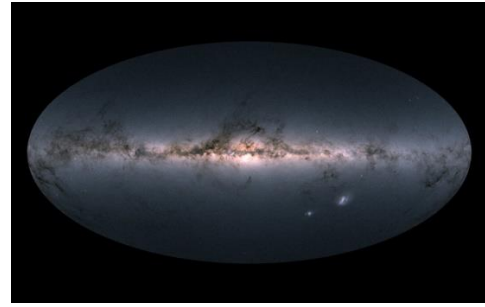
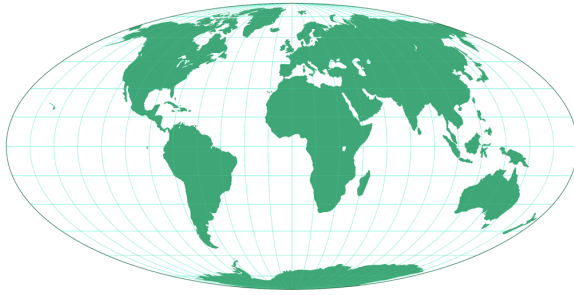
The graph below is a simplified version of the same data:



Why does this graph support or not support your conclusions in the previous questions? Justify your answer with evidence and reasoning from both this graph and the work you did previously.

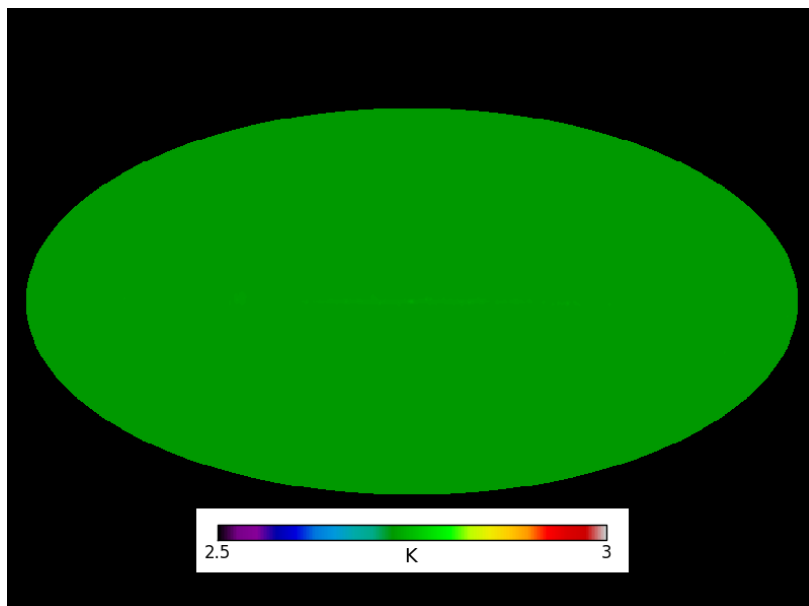
An example of a sufficient answer might be: The peak wavelength of the light detected by FIRAS was about 1000μm, which is in the microwave part of the EM spectrum. This is about a thousand times longer than the peak wavelength of infrared light at 3600K. So the FIRAS graph does support the idea that the infrared light from the early universe was extremely redshifted.

- B. Below are two maps that use a “Mollweide” projection map, which is a useful way to show the entire surface of a sphere. At left is a Mollweide projection of Earth, and at right is a Mollweide projection of the entire night sky using visible light.



Above left: Mollweide map projection of Earth. Source: map-projections.net Above right: The entire night sky from the GAIA telescope. Source: ESA

A skeptic might complain that this microwave light measured by COBE is simply being emitted all the time by the galaxies in the universe, and therefore is not 13 billion-year-old light! The final map is a Mollweide projection that uses microwave light rather than visible light. How does this image prove that galaxies are **not** the source of the signal measured by COBE?



Above: The highly uniform temperature of the CMB at 2.7 degrees Kelvin. Source: Dr. Katie Harrington, Univ. of Michigan

Answer: If the 1000 μ m light were coming from galaxies, then you would expect bright spots scattered all over the map from the nearby galaxies. There aren't any bright spots, the light is coming from everywhere at the same temperature. So it's not coming from galaxies. **Note to teacher:** a student with sharp eyes may notice a faint bright line across the middle – this is coming from the plane of the Milky Way!

- C. The light measured in the graphs and picture above is usually called the “Cosmic Microwave Background” or simply CMB. In a paragraph or two, explain why the CMB is a strong piece of

evidence for the Big Bang model of an expanding universe. Be sure to cite evidence for your explanation using the information from this assignment, and justify your evidence with reasoning.

An example of a highly proficient paragraph-length response:

We have evidence that the universe is expanding based on redshifted galaxies. Physicists realized that if this model of expansion were true, then there would be a time in the early universe when it was too hot and dense for atoms to even form. This hot and dense universe would constantly be emitting a lot of light. Once the universe expanded and cooled enough for hydrogen to form, its temperature would be about 3000 degrees Kelvin so the light would be infrared light. Over time, this infrared light would become extremely redshifted and would seem to come from everywhere. This is exactly what we see: microwave light at a temperature of 2.7 degrees Kelvin that comes from everywhere at once. The presence of this light supports the idea of an expanding universe.

Extension

1. When you do an image search for the CMB, you don't usually get the solid color shown in the Mollweide map in Figure 6. Instead, you get something that looks like Figure 7, which is called a "differential" measurement of the CMB.
 - a. What do you think the word "differential" means here? (*Hint: compare the scales in figures 6 and 7.*)

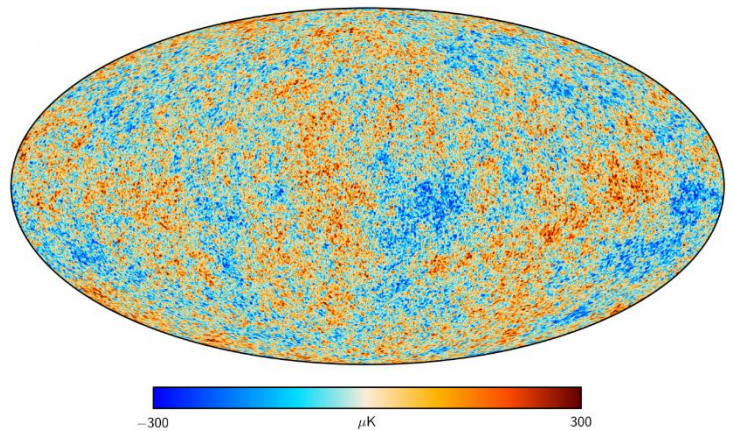


Figure 1: A differential map of the CMB from the Planck telescope.
Source: esa.int

Answer: A differential map is only showing the small differences between the different parts of the map. The whole sky is still 2.7 degrees Kelvin but this map is showing small differences about 10,000 times smaller than that.

- b. Why are scientists so interested in these tiny differences in the temperature of the CMB? What can be learned by analyzing these maps? (*try reading about the NASA telescope called WMAP here: https://map.gsfc.nasa.gov/mission/sgoals_universe.html*)

Answer: These maps provide stronger evidence for the Big Bang model and also give us a lot of information about what the early universe was like. We can learn about what the universe is made of and get hints that there are other types of matter and energy we haven't detected yet and know very little about (dark matter and dark energy).

Analyzing these details allows us to trace the universe all the way back to the first one-billionth of a second after the Big Bang.

Note to teacher: some additional interesting ideas for discussion with students might include the following:

- The large hot and cold “blobs” are thought to be traces of slight irregularities in the density of the universe at the moment of the Big Bang. These so-called quantum fluctuations, which initially appeared on a very tiny scale, have been “frozen” into the density of galaxies today on a huge scale!*
- By analyzing the hot and cold spots and getting a sense of the “average size” of a hot spot, we see evidence for dark matter: in the early universe, dark matter was pulling ordinary matter back inwards, but the hot radiation pressure of the ordinary matter would push it back out. This push-pull caused a set of ripples to form in the universe, which also became “frozen” into the structure of the universe.*
- Just like a slinky that can be shaken up/down or left/right as waves move from one side to the other, light can be polarized so that it only vibrates up/down or left/right. By measuring the polarization of the CMB light, physicists are trying to get glimpses of a time even earlier and closer to the Big Bang. If certain types of polarization are detected, this could answer questions about why the universe is so uniform and why its expansion is not faster or slower. This is the mission of the CLASS telescope, whose funding provided these instructional materials for you to use!*