STORIES IN THE WAVES: AN INTRODUCTION TO THE ELECTROMAGNETIC SPECTRUM, WITH A GRAVITATIONAL WAVE BONUS

INSTRUCTOR'S EDITION

INTRODUCTION: When you look at the "All Sky View," you get lots of different views of the same regions. Some are probably familiar looking, but others are quite bizarre.

So what are you looking at? And why does it all look so different?

When we think of "light" we tend to think of that which we can observe – visible light. In astronomy, when we refer to light we are referring to electromagnetic radiation, an oscillating electromagnetic field that propagates through space, carrying energy with it. While the exact nature of electromagnetic radiation is a bit unintuitive (Is it a wave? Is it a particle? Is it both, or neither? The answer is "Yes!"), we can ascribe properties of a wave to light. Different types of light have different wavelengths (the length over which the oscillation repeats itself) and different frequencies (how often a wave "peaks"). One thing that all types of light have in common is that, in a vacuum, they all move at the same speed: the speed of light (300,000 km/s). The speed of a wave is equal to its wavelength multiplied by its frequency. Due to this relation, light with longer wavelengths also has shorter frequencies.

Objects in the universe emit all different types of light, across the entire electromagnetic spectrum. If we limit ourselves to observing only what can be observed with our eyes, the visible portion of the spectrum, then we would severely limit what we can detect, and therefore learn, about our universe. This is why astronomers build telescopes that can observe in different wavelength ranges. Unfortunately, our Earth's atmosphere is not transparent to most wavelengths, which is why most telescopes that observe at wavelengths other than in the visible range need to be located in outer space, above the Earth's atmosphere.

But now astronomers have gravitational waves as well as electromagnetic waves to help them understand the universe, and sometimes we have been lucky enough to get information from both types of waves coming from the same event.

ANSWERS AND INSTRUCTIONS FOR THE TEACHER ARE GIVEN IN ALL CAPS.

MATERIALS:

Smartphone and SCIVR app
Computer and internet access for instructor
Projector

LEARNING OBJECTIVES:

Students will explore how different wavelengths of the electromagnetic spectrum are used to gain information about the properties of components in the universe.

Students will recognize the importance of space telescopes to the collection of astronomical data across the electromagnetic spectrum

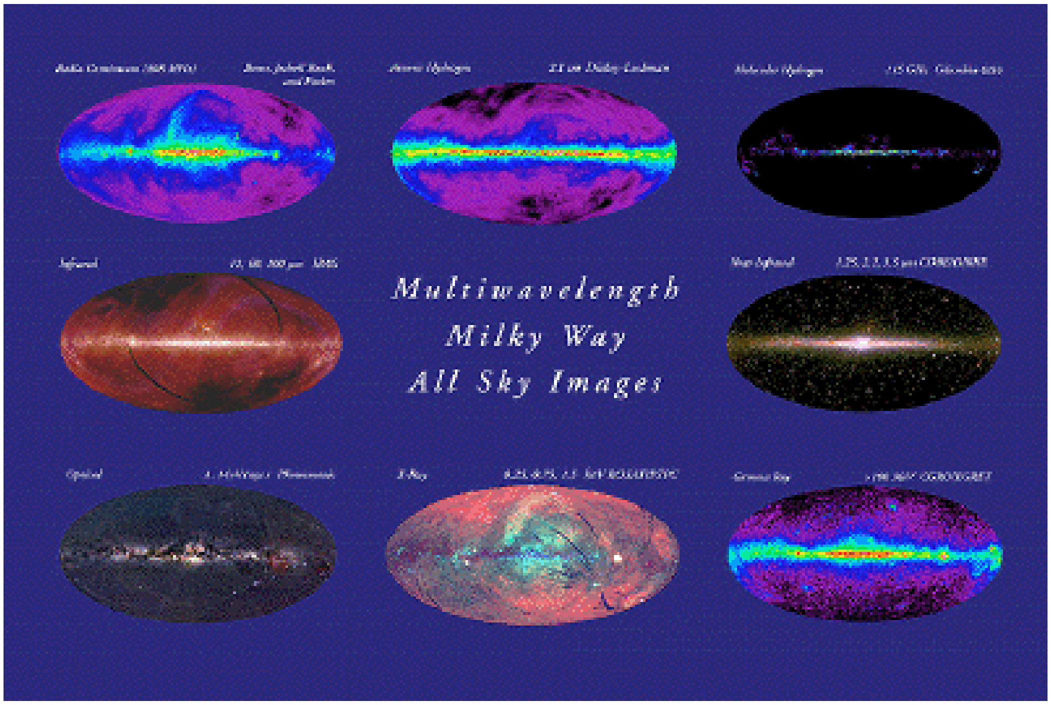
Students will be able to infer information about gravitational waves and GW sources based on the detection or non-detection of EM radiation.

EVALUATION:

Students are required to answer several questions within the activity. The activity itself could be collected as a worksheet and these questions graded for accuracy, or the questions could be fashioned into personal response questions and discussion questions embedded in a guided lecture (e.g., Powerpoint presentation). Questions could also be incorporated in quizzes/exams. Instructors are encouraged to listen closely to the conversations of student groups to find out if there are any persistent misconceptions or any confusion about the activity.

Engage:

IF ACCESS TO THE ALL-SKY VIEW IN THE SCIVR APP IS AVAILABLE, LET STUDENTS EXPLORE THE VARIOUS WAVELENGTH DOMAINS AND READ THE INFORMATION GIVEN. IF NOT, SHOW THE STUDENTS SCREENSHOTS FROM THE APP (SEE PRESENTATION), ALONG WITH THE FOLLOWING IMAGE. A HIGHER RESOLUTION VERSION IS INCLUDED IN THE ACCOMPANYING POWERPOINT PRESENTATION. NOW HAVE THE STUDENTS ANSWER THE FOLLOWING QUESTIONS.



(http://mwmw.gsfc.nasa.gov/mmw_allsky.html)

1. Look at the views of the sky in various wavelengths and compare and contrast the images. How are they similar? How are they different?
2. Are there any features that show up in some wavelengths but not in others?
3. Can you find the centre of our Galaxy?

The eight images shown are 360-degree images taken of our Galaxy from our vantage point on Earth. Each oval represents the entire sky surrounding the Earth. It is similar to maps of the Earth where they represent the surface of the Earth as a flat two-dimensional image. The difference is, for a map of the Earth, we are looking at the surface from outside of the Earth. For our Galaxy, we are looking at it from inside.

In each image, the center of our Galaxy is located in the center of the image. The horizontal line across the center of the ovals represents the plane of our Galaxy. Where this is an all-sky view, if you continue off one side of the image it would wrap around to the other side in one continuous loop. Points above and below the center of the image correspond to regions above and below the Galaxy's plane, respectively.

It turns out that each image is of the same object, but was taken in a different wavelength range.

4. In which wavelength range do you seem to observe the greatest amount of information?

5. In which wavelength range do you seem to observe the smallest amount of information?

6. If all we observed were what we can see with our eyes (the visible range), would we have a complete picture?

7. What can you observe in other images that is missing in the visible light image? Be specific about WHICH image you're discussing.

STUDENTS SHOULD BE ABLE TO SEE RIGHT AWAY THAT THE IMAGES SHOW AN INTENSE LINE THAT REPRESENTS THE DISK OF OUR GALAXY. THEY MIGHT ALSO COMMENT THAT IN SOME IMAGES, THE 'COLORS' ARE SIMILAR. THIS IS A GOOD TIME TO TALK ABOUT ENHANCED COLORS (SOMETIMES REFERRED TO AS 'FALSE COLORS'). BECAUSE OUR EYES CANNOT OBSERVE THESE WAVELENGTHS, ASTRONOMERS MUST ASSIGN DIFFERENT COLORS TO DIFFERENT INTENSITIES TO CREATE A VISUAL REPRESENTATION OF SOMETHING THAT WE CANNOT ACTUALLY SEE.

SOME DIFFERENCES THAT MIGHT BE MENTIONED IS THAT WHAT IS BRIGHT IN SOME IMAGES IS BLACK IN OTHERS (E.G., THE DARK LANES ACROSS THE GALACTIC DISK IN THE VISIBLE IMAGES IS ACTUALLY QUITE BRIGHT IN THE INFRARED AND RADIO IMAGES). THE DARK LANES CORRESPOND TO DUST THAT BLOCKS VISIBLE LIGHT, BUT RADIATES STRONGLY IN THE LONGER WAVELENGTHS. ALSO THERE ARE REGIONS WHERE THE INSTRUMENTS DO NOT HAVE COMPLETE COVERAGE, SO THERE ARE BLACK STREAKS AND EMPTY REGIONS.

STUDENTS MIGHT ALSO NOTICE AN ARC OF MATERIAL IN THE RADIO WAVE VIEW THAT DOES NOT SEEM TO HAVE ANY CORRESPONDING STRUCTURE IN THE VISIBLE IMAGE, TELLING ASTRONOMERS ABOUT A FEATURE THAT WE WOULD NOT KNOW ABOUT IF WE OBSERVED ONLY IN VISIBLE LIGHT.

Explore:

TO INVESTIGATE THE ROLE OF MULTIWAVELENGTH ASTRONOMY, SHOW THE STUDENTS THE VIDEO “MORE THAN YOUR EYES CAN SEE,” WHICH CAN BE FOUND HERE: http://coolcosmos.ipac.caltech.edu/videos/more_than_your/

WHILE WATCHING THE MOVIE, STOP PERIODICALLY AND ASK YOUR STUDENTS TO ***PREDICT*** WHAT WILL HAPPEN NEXT OR TO EXPLAIN WHAT THEY SEE. THE TIMES LISTED BELOW CORRESPOND TO VIDEO TIMES AT WHICH YOU SHOULD STOP AND ASK THE QUESTIONS.

6. (1:54) Which side of the narrator is hotter? Which side is cooler? How can you tell?

ANS The side closer to the fire is hotter. You can tell because it appears brighter (more yellow).

7. (2:12) Why can’t you see the person in infrared light when she is below the surface of the water?

ANS Water is opaque to infrared light, it cannot pass through, and so our view of the person is blocked.

8. (3:10) How do you think a cold-blooded reptile will look in the infrared?

ANS Cold-blooded animals still have a body temperature, and therefore still radiate heat.

9. (3:14) What about giraffes? Will their dark spots appear darker or brighter in the infrared?

ANS Their dark spots will appear brighter in the infrared.

10. (3:17) Why do you think the dark spots appear brighter in the infrared?

ANS Since dark colors absorb more sunlight than light colors, their dark spots will actually appear brighter in the infrared.

11. (3:19) How do you think the horns of an animal compare to the rest of its body in the infrared?

ANS Horns appear cooler than the rest of the animal's body.

12. (3:35) Based on what we learned about giraffes, looking at the zebra in the infrared, which color do you think corresponds to the black stripes and which to the white?

ANS The brighter stripes in the infrared correspond to the black stripes. INTERESTINGLY THIS IS SIMILAR TO THE DARK DUST LANES IN THE GALAXY, WHICH VISIBLY ABSORB LIGHT, BUT RADIATE STRONGLY IN THE INFRARED DUE TO THE FACT THAT THE MATERIAL IS HEATING.

13. (3:51) Do you think the horns of the rhinoceros are the same as the horns of the ibex we saw before?

ANS The horns of the rhino are actually rather warm compared to its body.

Explain:

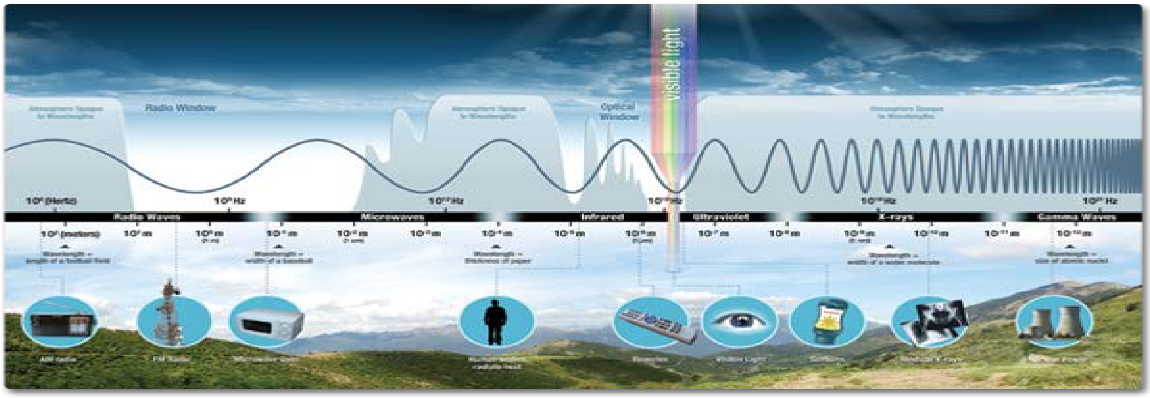
Because our eyes are limited by what they can detect, and because different types of light are either transmitted or blocked by different materials, we must observe the sky in multiple wavelengths. By studying celestial objects at different wavelengths, we can get a bigger picture of what is out there and what is going on than if we only observed at visible wavelengths.

One of the greatest problems for observing in visible light is dust. Interstellar dust is roughly the same size as the wavelength of visible light. As a result, dust will block visible light, preventing it from passing through space.

REVISIT THE VISIBLE IMAGE OF THE GALAXY AND POINT OUT ALL THE DARK PATCHES IN THE PLANE OF THE GALAXY. THESE ARE ALL DUST CLOUDS BLOCKING OUR VIEW.

As we look out into space, we can only see so much because dust blocks our view in certain directions. By observing in other wavelengths though, we can see beyond interstellar dust because while it may block visible light, it doesn't block other wavelengths of light.

Atmospheric Windows



(http://missionscience.nasa.gov/images/ems/emsIntro_mainContent_Electromagnetic_Spectrum.png)

We discovered that for many objects, certain wavelengths of light can pass through while other wavelengths are blocked. Earth's atmosphere behaves the same way. Due to molecules in the Earth's atmosphere, some wavelengths of light can easily pass through while others are absorbed or scattered.

14. Looking at the image above, which wavelength ranges easily make it through the Earth's atmosphere down to the surface?

VISIBLE LIGHT AND RADIO WAVES PASS EASILY THROUGH THE EARTH'S ATMOSPHERE. THE ATMOSPHERE IS ESSENTIALLY TRANSPARENT TO THESE TYPES OF LIGHT.

15. Which wavelength ranges are completely blocked by the Earth's atmosphere?
XRAYS AND GAMMA RAYS ARE COMPLETELY BLOCKED.

16. Which wavelength ranges are partially blocked?

IR AND UV ARE PARTIALLY BLOCKED. THE ATMOSPHERE IS PARTIALLY TRANSPARENT TO THESE TYPES OF LIGHT.

Because many wavelengths of light can't reach the Earth's surface, it is important to deploy telescopes into space, above the Earth's atmosphere, so we can see the Universe in all wavelengths. A partial list of NASA Astrophysics missions is included below. A more complete list can be found at http://science.nasa.gov/astrophysics/missions/

Microwave:

Planck – http://planck.caltech.edu/

Wilkinson Microwave Anisotropy Probe (WMAP) – http://map.gsfc.nasa.gov/

Infrared:

Hubble Space Telescope (HST) – http://hubble.nasa.gov/
Spitzer Space Telescope – http://spitzer.caltech.edu/

Visible:

Hubble Space Telescope (HST) – http://hubble.nasa.gov/
Keck Interferometer – http://planetquest.jpl.nasa.gov/Keck/keck_index.cfm
Kepler – http://kepler.nasa.gov/

Ultraviolet:

Far Ultraviolet Spectroscopic Explorer (FUSE) – http://fuse.pha.jhu.edu/
Hubble Space Telescope (HST) – http://hubble.nasa.gov/

X-ray:

Chandra X-Ray Observatory – chandra.harvard.edu
Nuclear Spectroscopic Telescope Array (NuSTAR)
– http://www.nustar.caltech.edu/
Suzaku – http://heasarc.gsfc.nasa.gov/docs/astroe/astroegof.html
X-ray Multi-Mirror (XMM) Mission
– http://heasarc.gsfc.nasa.gov/docs/xmm/xmmgof.html

Gamma Ray:

Fermi – http://fermi.gsfc.nasa.gov/
Swift Gamma Ray Burst Explorer – http://swift.gsfc.nasa.gov/

BUT WHAT ABOUT GRAVITATIONAL WAVE ASTRONOMY?

Unlike light waves, gravitational waves are ridiculously hard to detect. Light waves result from the interplay between electricity and magnetism, forces that are a hundred trillion trillion trillion times stronger than gravity. Those waves bound around the universe, interacting with all the charged particles they encounter. As a result, it's practically child's play to create something that generates radio waves. Just hook up a battery to a wire, and then unhook it, then hook it up again, and repeat. Or find a capacitor and inductor and make them do the oscillating work for you. As it turns out, charged particles, like siblings, really enjoy bothering each other, so this simple radio transmission could easily be picked up by a receiver and translated.

But masses are much more timid, their voices carrying as fast and as far as light waves, but at a much, much, much lower volume. By "volume," we don't mean literal loudness. What we measure is the compressing and stretching of the tapestry that makes up spacetime. Still, all the analogies and animations you've watched make it appear as though swells comparable to those encountered in a wicked storm at sea were sweep through our neighborhood. Yet it took a century and every scrap of scientific ingenuity we possessed to devise and build a detector to listen in on the unfathomable energy released cosmic collisions. The first gravitational wave event discovered – GW150914 – sent out more power in gravitational waves than the <u>total</u> power of

Every.
Single.
Star.
In.
The.
Observable.
Universe.

We've seen individual stars explode ten times farther away than GW150914, and those events released far less energy.

Interestingly, there was not a hint that the GW150914 event emitted ANY electromagnetic radiation.

17. Knowing what you currently know about electromagnetic radiation, what does this tell you about the OBJECTS involved in that event?

In 2017, the gravitational wave event GW170817 was coincident with detections in radio waves, infrared, visible, ultraviolet and x-rays. In fact, two seconds after the culmination of the event, the Fermi Gamma Ray satellite detected a short burst of gamma rays. It was determined that the event occurred in a galaxy 144 million light years away.

What this means is that dinosaurs were roaming our planet when the gravitational waves and the electromagnetic waves were emitted from their source, and after spending 144 million years zipping through space, they finally arrived at our various detectors.

18. Knowing what you currently know about electromagnetic radiation, what can you say about the SPEED of gravitational waves compared to the speed of light?

GRAVITATIONAL WAVES MOVE AT THE SPEED OF LIGHT. IF THEY DIDN’T, WE WOULD NOT HAVE HAD SUCH A COINCIDENCE IN THE TIMING.

19. Knowing what you currently know about electromagnetic radiation, what do you expect to be different about the GW170817 source compared to the GW150914 source?

SINCE THE GW150914 SOURCE DIDN’T PRODUCE EM RADIATION, IT DIDN’T INVOLVE SIGNIFICANT AMOUNTS OF NORMAL MATTER. INDEED IT INVOLVED MERGING BLACK HOLES, WHICH EMIT NO LIGHT AT ALL. HOWEVER THE GW170817 EVEN PRODUCED EM RADIATION ACROSS THE ENTIRE EM SPECTRUM, MEANING THAT THERE HAD TO BE ORDINARY MATTER INVOLVED. SCIENTISTS HAVE CONCLUDED THAT GW170817 SOURCE WAS A BINARY NEUTRON STAR THAT MERGED TO FORM EITHER THE MOST MASSIVE NEUTRON STAR KNOWN OR THE LEAST MASSIVE BLACK HOLE. STAY TUNED FOR MORE DEVELOPMENTS ON THIS FASCINATING OBJECT.