5E Lesson Plan

Topic: Gravitational Wave Astronomy

Title: Extraction and analysis of astrophysical data from coalescing black holes.

Time: 4 x 80 minute lesson.

Grade: IB Physics (Grade 11)

<table>
<tr><th colspan="2">Standards</th></tr>
<tr><td>Common Core</td><td>Understand solving equations as a process of reasoning and explain the reasoning.
CCSS.MATH.CONTENT.HSA.REI.A.1
Explain each step in solving a simple equation as following from the equality of numbers asserted at the previous step, starting from the assumption that the original equation has a solution. Construct a viable argument to justify a solution method.

Model periodic phenomena with trigonometric functions.
CCSS.MATH.CONTENT.HSF.TF.B.5
Choose trigonometric functions to model periodic phenomena with specified amplitude and frequency.</td></tr>
<tr><td>NGSS</td><td>HS-ETS1-2: Design a solution to a complex real-world problem by breaking it down into smaller, more manageable problems that can be solved through engineering.

HS-PS4-5: Communicate technical information about how some technological devices use the principles of wave behavior and wave interactions with matter to transmit and capture information and energy.</td></tr>
<tr><td>International Baccalaureate</td><td>Understandings:
Traveling waves, wavelength, frequency, time period and wave speed.
Amplitude, displacement, and phase difference
Angular displacement and angular velocity.
Interference
Principle of superposition
Black holes</td></tr>
<tr><td colspan="2">The activity connects to these aspects of physical science:
Aspects of the scientific method that deal with data analysis and forming conclusions from data
Properties and behavior of waves
The use of mathematics in scientific investigations
Wave behavior and properties including the nature of light, development of scientific investigations, the use of technology in investigations, formulating and revising scientific explanations and models, safe practices in investigations.</td></tr>
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Background and Justification

I have chosen an activity that uses data collected from the Laser Interferometer Gravitational wave Observatory (LIGO) on the coalescence of two black holes. I have chosen this data set for the following reasons:

- Connects multiple topics in science covered in the International Baccalaureate Physics diploma course (Waves, Circular motion, Astrophysics)
- Students have to use Mathematics when conducting their analysis and investigation.
- Students can apply what they learn to design and build their own Michelson Interferometer to collect data (engineering).

The above reasons result in a data driven activity that integrates the STEM disciplines. I would complete this activity during the Waves topic because it will help students learn about the wave behavior in an authentic manner. Using relevant data from a recent scientific discovery of the merging of black holes should help inspire young minds and place wave knowledge into an engaging context. We would have also covered the circular motion topic, which will help connect the related mathematics between circular motion and wave motion. The data would provide students with an opportunity to make connections between topics. The data activity also provides a suitable segway into the Astrophysics topic, particularly cosmology and stellar distances.

Learning Objectives:

1. Students will describe the changes that occur in gravitational waves emitted from a compact binary system as the system moves towards coalescence.
2. Students will analyse data from gravitational wave measurements and use relevant equations to calculate the chirp masses and astronomical distances of binary systems.
3. Students will describe the process that scientists would use to extract information about astrophysical sources from gravitational wave data.
4. Students will demonstrate the manual skill that is required to build a precision device
5. Students will explain light interference using the basic model of wave behavior
6. Students will describe the relationship between the movement of an interferometer mirror and the resulting movement of the pattern of fringes

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Materials needed:

Each student or group of students should receive a copy of each of the four data plots:

- Far From Coalescence
- Last Second Before Coalescence
- 1.0 Second Before Coalescence
- 0.1 Second Before Coalescence

Each student should receive a copy of the Student Worksheet for the activity

- Download Student Worksheet
- Download the Teacher's Guide

Materials needed to build Michelson Interferometer

- Base plate
- Laser
- Mirror on Adjustable Mount
- Aluminum Angle for Fixed Mounts
- Mirror on fixed mount
- Beam Splitter on Fixed Mount
- Small diverging lens
- 5-minute Epoxy

ENGAGE

Prompt - Your body has been stretched and squeezed without you realizing it!

Read the article from Physics World: A Wave of Discovery to help address the discussion question.

Watch Einstein's Messengers and pay attention to the following:

- 2:12: "From the fiery collision of neutron stars . . ." Viewers see a simulation of the merger of a pair of neutron stars. This is the type of event discussed in the activity that would give rise to the gravitational wave data plots that the students will use.
- 4:15: Another merger simulation. "When a massive object collides with another, it causes waves in the fabric of space-time." As the simulation illustrates, the gravitational waves arise well before the collision, or coalescence, occurs. The changes that occur in the wave pattern as coalescence approaches are evident in the activity's data plots.
- 4:30: ". . . These waves travel outwards from the source, carrying information about the events that caused them." In the activity students will learn how to extract some of the information that the waves carry, such as the mass of the source and its distance from earth.
- 5:00 "You get exactly what happened at the source." This comment is another instance of the notion that gravitational waves tell a story about the bodies and processes that released them. In the activity students will learn how to decode part of the story.
- 9:45: "These small effects are coming from these big masses far away -- black holes, neutron stars -- we will see things happening in the universe by measuring these small effects."
- 14:25 "Take neutron stars in the act of merging. They make a wonderful chirp. It's a cosmic chirp." The chirp signal produced by an inspiral event forms the basis of this classroom activity.

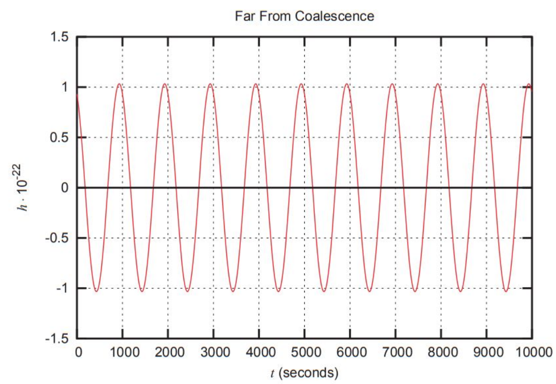
Discussion - In pairs

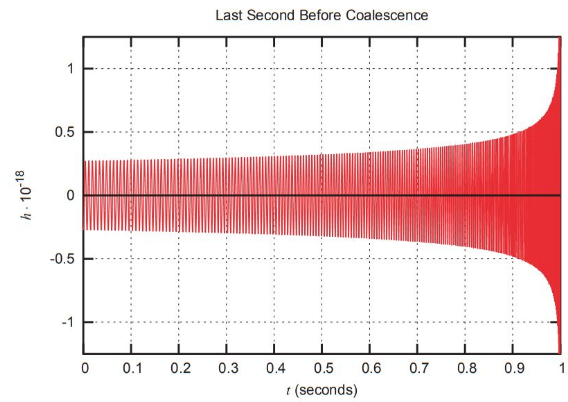
Now that you have explored the world of gravitational waves discuss the validity of the prompt. Consider when and how did this happened?

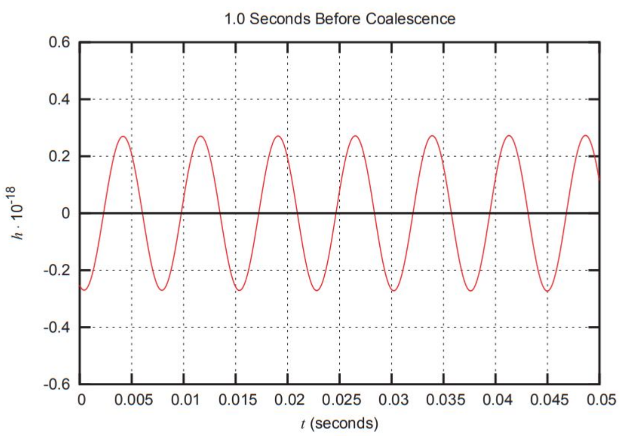
EXPLORE

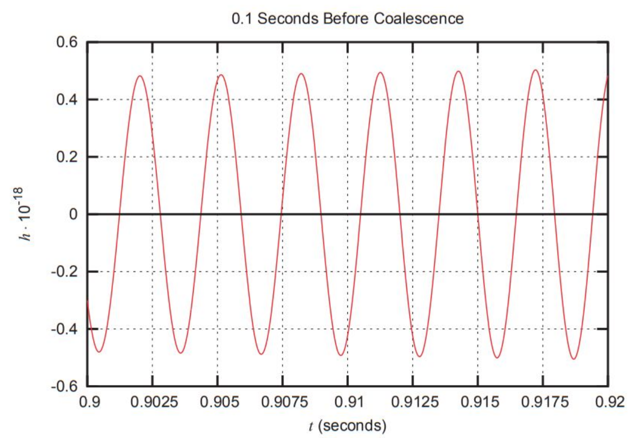
Part 1: Examining the data

Students will be given access to the the four data plots in the table below:









Students will examine the plots to collect qualitative and quantitative data and record it in the table below and consider the accopained questions.

The Name of the Data Plot	Describe the plot's appearance	Measure the gravitational wave period (seconds)	Measure the gravitational wave frequency (Hz)	Measure the gravitational wave amplitude, *h*
Far from Coalescence (a million years until coalescence occurs)	**Smooth cosine, unchanging amplitude and period**	**1000 s**	**0.001 Hz**	**1 x 10^{-22}**
1.0 Second Before Coalescence	**The amplitude has increased; the priods are shorter**	**0.0075 s**	**133 Hz**	**2.5 x 10^{-19}**
0.1 Second Before Coalescence	**You can see a change in amplitude from one side of the plot to the other**	**0.0030 s**	**333 Hz**	**5 x 10^{-19}**
Last Second Before Coalescence	***How do the wave periods and amplitudes change on this plot?*** **The periods shrink with the passage of time across the plot and the amplitude grows, slowly in the first fractions of a second then significantly at the end**			

1. How does the data change as the binary system moves towards coalescence?

2. What is happening in the binary system that causes these changes in the gravitational wave data?

Part 2: Using Gravitational Wave Mathematics

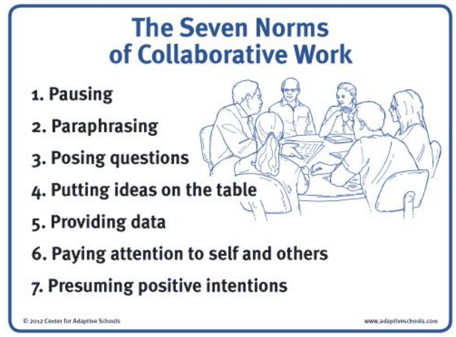
Follow the prompts and equations in part 2 of the student sheet to calculate:

1. Orbital separation and distance to the binary system using a mass approximation
2. Distance to the binary system with a calculated chirp mass

Part 3: Design and build a Michelson Interferometer

Design prompt - With the materials provided design and build a michelson interferometer.

Students will complete this design task in groups of four. In addition to the learning objective related to this task students will be assessed on their ability to collaborate effectively in this task. Ensure students are aware of the norms of collaboration before starting the task.



EXPLAIN

Consider the question related to the processed gravitational wave data.

1. Write a conclusion in which you describe what you have learned from your work in the activity.

2. What are some specific ideas or skills that you have learned or improved upon?

3. What information did you learn by doing the calculations?

4. What insights did you gain about the process of analyzing gravitational wave data?

Consider the question related to building the Michelson Interferometer

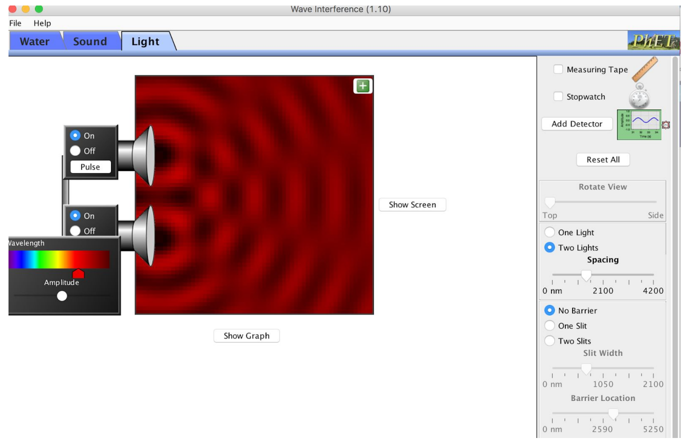
5. If you move the interferometer adjustable mirror by the slightest amount, the pattern of fringes changes, and eventually it goes away.

6. Why is the instrument so sensitive to the position of the mirror?

7. Interferometers can be used to measure movements that are much, much smaller that you would measure with tools such as rulers. Using your experience of pulling on the mirror, explain how this is possible.

ELABORATE

Students now need to be given the opportunity to elaborate on the physics behind to the functioning of LIGO and their own Michelson Interferometer. To support students they will be prompted to explore a [Phet simulation] and the [Physics classroom]. Then consider the following questions:



1. What do we mean by 'light interference'?

2. Is light the only type of wave that can undergo interference?

3. Describe the two types of wave interference.

4. Use the concept of interference to explain how the interferometer works.

5. What are the similarities and difference between the interferometer you built and LIGO?

EVALUATE

Part 1: Peer assessment and reflection

Student will have the opportunity to peer assess each others work. Students will be deliberately paired with peers of similar cognitive ability to promote deep level thinking. Students will use the following single point assessment rubric to evaluate weather the learning objectives have been met. Students will then have the opportunity to reflect on the feedback given to them and make modifications to their work before final submission.

Rubric - Gravitational Wave Astronomy Name:___________________________

1 = standard not met; **2** = standard partially met; **3** = standard met; **4** = exceeds expectations

Gravitational Wave Astronomy					
Assessment Criteria	**1**	**2**	**3**	**4**	**Feedback**
Describe the changes that occur in gravitational waves emitted from a compact binary system as the system moves towards coalescence.					
Analyse data from gravitational wave measurements and use relevant equations to calculate the chirp masses and astronomical distances of binary systems.					
Describe the process that scientists would use to extract information about astrophysical sources from gravitational wave data.					
Demonstrate the manual skill that is required to build a precision device					
Explain light interference using the basic model of wave behavior					
Describe the relationship between the movement of an interferometer mirror and the resulting movement of the pattern of fringes					
Level: **19+**=L7; **18**=L6; **16+**=L5; **14+**=L4; **12+**=L3; **8+**=L2; **6+**=L1	**Total -**				**Overall level-**

Part 2: Self assessment and reflection

Students will then self assess their ability to collaborate during the design task. Students will also write a reflection on what their own strengths and weakness were when completing the collaborative design task. Self assessment will be completed with the following rubric:

COLLABORATION RUBRIC
(for secondary and upper elementary grades)

	Below Standard	Approaching Standard	At Standard	Above Standard
Responsibility for Oneself	▸ is not prepared and ready to work with the team ▸ does not do project tasks ▸ does not complete tasks on time ▸ does not use feedback from others to improve his/her work	▸ is sometimes prepared and ready to work with the team ▸ does some project tasks, but needs to be reminded ▸ competes some tasks on time ▸ sometimes uses feedback from others	▸ is prepared and ready to work with the team; is available for meetings and uses the team's communication system ▸ does what he or she is supposed to do without having to be reminded ▸ completes tasks on time ▸ uses feedback from others to improve his or her work	*In addition to* ***At Standard*** *criteria:* ✚ does more than what he or she has to do ✚ asks for additional feedback to improve his or her work, beyond what everyone has been given
Helping the Team	▸ does not help the team solve problems; may cause problems ▸ does not share ideas with other team members ▸ does not give useful feedback to others ▸ does not offer to help others	▸ cooperates with the team but does not actively help it ▸ makes some effort to share ideas with the team ▸ sometimes gives useful feedback to others ▸ sometimes offers to help others	▸ helps the team solve problems, manage conflicts, and stay focused and organized ▸ shares ideas that help the team improve its work ▸ gives useful feedback (specific and supportive) to others so they can improve their work ▸ offers to help others do their work if they need it	*In addition to* ***At Standard*** *criteria:* ✚ steps in to help the team when another member is absent ✚ encourages others to share ideas, helps to make them clear, and connects them to the team's work ✚ notices if a team member does not understand something and takes action to help
Respect for Others	▸ does not pay attention to what teammates are talking about ▸ does not show respect for teammates (may interrupt, ignore ideas, hurt feelings)	▸ usually listens to teammates, but not always ▸ is polite and kind to teammates most of the time, but not always	▸ listens carefully to teammates ▸ is polite and kind to teammates	*In addition to* ***At Standard*** *criteria:* ✚ encourages the team to be respectful to each other ✚ recognizes everyone's strengths and encourages the team to use them

Part 3: Final submission

After students have had an opportunity to make modifications based on the feedback from their peers the will submit their work for a final grade which will be assessed with the aforementioned rubrics. Feedback will be given to students in a timely manner.

Bibliography

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