What Happens to Waves Near Black Holes?

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Received January 17, 2024
Accepted July 26, 2024
Electronic access August 31, 2024

This study presents a comprehensive literature review investigating the impact of black holes on waves, specifically focusing on the influence of intense gravitational fields on energy-carrying mediums. The research aims to bridge the gap in understanding how extreme gravitational fields affect and change wave behaviours and features. The paper uses pictographs to discuss the sine function and electromagnetism, furthermore, the study elucidates the mathematical relationships between various physical quantities, and equations are employed to provide a precise understanding of these interactions. The paper concludes that when waves are near a black hole they can either become permanently undetectable or undergo alterations in their characteristics and features. This conclusion has significant implications for astrophysics. They challenge our understanding of wave behaviour in extreme gravitational fields and provide crucial tests for general relativity. These findings could refine our models of black hole dynamics and inform our knowledge of event horizons and singularities. Additionally, understanding these interactions aids future research that could focus on enhancing gravitational wave detection, exploring quantum gravity, improving black hole imaging, and creating advanced astrophysical simulations.

Introduction

Black holes are incredibly intriguing cosmic objects. They behave like super-strong cosmic vacuum cleaners that can even swallow light and other waves. Imagine you're near an incredibly powerful vacuum cleaner, and you toss small objects towards it. The closer the objects get to the vacuum cleaner the harder it sucks them in. Black holes have a similar effect on waves. So when waves an immovable object meets the irresistible force of a black hole what happens? Similar to tossing objects into a powerful vacuum cleaner, waves nearing black holes succumb to the gravitational force of a black hole, altering the waves trajectory and properties. This paper embarks on an exploration of the transformative journey waves undergo in the proximity of black holes. Understanding what happens to waves near black holes is important because it helps test fundamental physics theories such as general relativity and quantum mechanics, in extreme gravitational environments. Observations of wave behaviour near black holes can confirm or challenge existing theoretical predictions, advancing our understanding of the universe's fundamental laws. Waves near black holes also play a significant role in various astrophysical processes like the evolution of galaxies. Understanding how waves interact with black holes is crucial for unravelling these complex phenomena and their impact on the formation and evolution of cosmic structures. Through a meticulous review of existing literature, the paper will explore the fundamental principles governing black hole dynamics and explore waves. Firstly, the paper discusses the sine function and delves into its mathematical significance in capturing the oscillatory nature of waves and their fundamental attributes. Through a detailed analysis facilitated by the sine function, the intricate characteristics of waves are meticulously delineated, laying the groundwork for a deeper comprehension of their transformative behaviours in close proximity to a black hole. Furthermore, the concept of electromagnetism is explained to provide a foundational understanding of electromagnetic waves, which is essential for grasping the phenomenon of redshift. The study also explores how electromagnetic and other types of waves can undergo significant changes when approaching a black hole. Most importantly Black holes are explained with the help of Einstein's theory of general relativity as it is crucial for comprehending the behaviour of waves near them because black holes fundamentally alter the fabric of spacetime. Waves interact uniquely with this warped spacetime. Therefore, a grasp of black hole concepts is essential for understanding how waves behave in these extreme conditions. Finally, the results are described by combining various concepts that this paper explains.

What The Sine Function Is and How Is It Used to Describe Waves

The sine function is essential to describe and understand waves because it serves as a fundamental mathematical tool for expressing oscillatory patterns. Waves exhibit repeating patterns over time, and the sine function, with its inherent periodicity, precisely captures this behaviour. Its characteristics, such as amplitude and frequency, align with key properties of waves, providing a concise mathematical form to describe waves, more-over the application of the sine function enhances our ability to express the dynamics of waves in the complex gravitational fields like black holes.

The sine is defined as the ratio of the side opposite to θ to the hypotenuse, in a right-angled triangle. The sine of an angle θ is calculated by considering a right-angled triangle, in which one of the angles is $0^\circ \leq \theta \leq 90^\circ$.

The equation of the Sine:

$$\sin(\theta) = \frac{o}{h}$$

where:

- $o =$ opposite side of the angle θ
- $h =$ the hypotenuse of the right-angled triangle

A property of this ratio is that it only depends on θ and not the size of the triangle. This property allows us to assign a real number to every angle within the range of $0^\circ \leq \theta \leq 90^\circ$, representing the sine value of that angle.

This definition can be expanded to cover angles within a broader range of $0^\circ \leq \theta \leq 360^\circ$, since these encompass all the values a possible angle can take. Therefore, a unit circle is utilized.

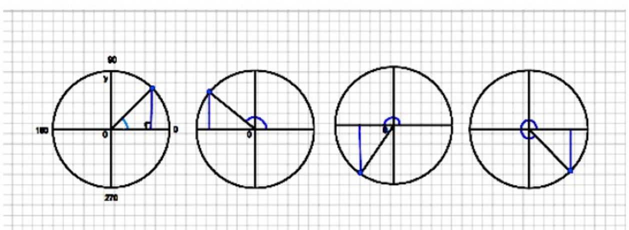

Fig. 1 A picture showing how y-coordinates of the blue point from the horizontal axis represent the sine function values for the different angles.

as the blue dot moves around the circle, the height of the vertical blue line from the horizontal axis changes periodically. The change in the vertical height value corresponds to the sine of the changing angle.Finally, it can be stated that the y-coordinates of the blue point from the horizontal axis represent the sine function values for the different angles. This relationship between the sine function and the unit circle aids in understanding the behaviour of the sine function, which is a periodical wave[1].

The oscillation of the y-coordinate as the angle of theta (θ) changes gives rise to the sinusoidal shape of the sine function.

Features of a Wave

The equation,

$$f(x) = A\sin\left(\frac{2\pi x}{W}\right)$$

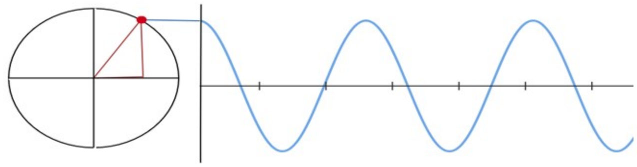

Fig. 2 Sine wave using the unit circle

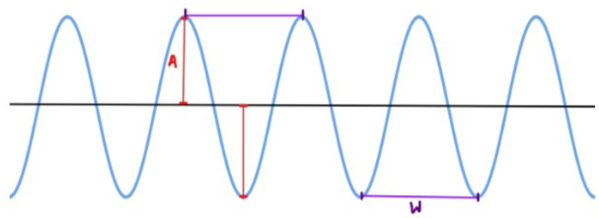

Fig. 3 A diagram showing the features of a wave
A= Amplitude
W= Wavelength

is plotted in the above diagram. It represents a sinusoidal function, where the wave features and characteristics below can be clearly expressed within the framework of this sinusoidal function.

Here, $f(x)$ is the value of the function at a given point x. A represents the amplitude of the wave. The term inside the sine function, $\left(\frac{2\pi x}{W}\right)$, determines the frequency and phase of the oscillation. x is the independent variable representing position along the x-axis, and W represents the wavelength of the wave.

Amplitude

The maximal distance that a particle in the medium is displaced from its equilibrium position. The amplitude of a wave is the distance from its resting position to either the highest point (crest) or the lowest point (trough).

Wavelength

The wavelength is the distance from the starting point of one wave to the same point on the next wave, or It is distance from one crest to the next.

Frequency

The frequency of a wave is the number of oscillations the wave undergoes in a certain period of time. Typically measured in hertz (Hz), where one hertz is equal to one cycle per second.

The wavelength and frequency of a wave are inversely proportional.

A formula that relates them: speed = frequency x wavelength.

If the wavelength increases, the frequency decreases. This happens because there would be less number of oscillations per unit time. If the wavelength decreases, the frequency increases. As more oscillations can fit within the same time period.

Electromagnetism

Electric Field

The electric field is a region around a charged particle[Q1]. If a charged particle[Q2] is inside the region of an electric field then the particle[Q2] experiences a force due to the field created by the charged particle[Q1].

Electric Force

The electric force is the force experienced between two charged particles or objects. If there are two oppositely charged particles(positive-negative), they are attracted to each other whereas if there are two similarly charged particles(negative-negative), (positive-positive) they repel each other. This force of attraction and repulsion is known as an electric force.

The force between two charged particles can be described by Coulomb's law.

This law states that the magnitude of electric force is directly proportional to the product of the magnitudes of the charges and inversely proportional to the square of the distance between them.

Electromagnetism

Electromagnetic waves are waves that consist of oscillating electric fields and magnetic fields. The oscillation of these electric and magnetic fields is perpendicular to each other. These waves are created when charged particles, such as electrons, accelerate or move back and forth. An example of an electromagnetic wave is visible light. There are other types of electromagnetic waves that are not directly visible to the human eye, e.g. infra-red, ultraviolet, ect. Their frequencies are not directly observable to humans due to the difference in wavelengths which are either higher or lower than the visible light spectrum. The spectrum consists of various colours, from violet (shorter wavelengths) to red (longer wavelengths). Each colour corresponds to a unique wavelength, with violet having the shortest and red having the longest.

Gravity

Gravity influences the paths and properties of waves. The curvature of spacetime, a central concept in Einstein's theory of gravity, is instrumental in comprehending the intricate interactions between waves and black holes.

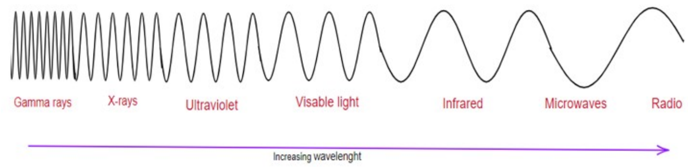

Fig. 4 Electromagnetic spectrum

Newton's Theory of Gravity

Newton described gravity as the force of attraction between any two objects in the universe. The strength of the force depends on the mass of an object and the distance between them. The larger the mass of an object, the stronger its gravitational pull. Similarly, the closer two objects are to each other, the stronger the gravitational force between them. Newton stated that this force is what makes things fall to the ground and keeps planets in their orbits around the Sun[2]. however, there were scientific challenges and problems with Newton's theory of gravity, because classical Newtonian gravity could not explain certain astronomical phenomena, such as the precession of Mercury's orbit and the bending of light around massive objects. Necessitating the development of a new concept for understanding gravity. Which was Einstein's theory of gravity.

Einstein's Theory of Gravity

Einstein's theory of gravity is known as the General Theory of Relativity. General Relativity describes gravity as the curvature of spacetime caused by the presence of mass and energy. Einstein proposed that massive objects, like planets and stars, curve and warp the fabric of spacetime around them. Resulting in other smaller objects follow curved paths due to the curvature of spacetime caused by massive objects, which gives the appearance of a gravitational force attracting the smaller object towards the massive object[3].

Red Shift

The red shift is when a wave stretches undergoing an increase in its wavelength. The stretching of wavelength causes the waves to shift towards the end of the spectrum.

For example: when an infrared wavelength stretches and transitions into a microwave wavelength.

When the wave propagates far away from the black hole, the value of W in the equation

$$f(x) = A\sin\left(\frac{2\pi x}{W}\right)$$

changes. This alteration in W, which signifies a longer wavelength, leads to a decrease in the frequency of the wave. The decrease in frequency results in a shift of the wave towards the longer-wavelength, resulting in a Redshift.

What are Black Holes?

Black holes are regions in space-time from which nothing, even light cannot escape. A black hole is formed when the core of a star, many times more massive than the sun, collapses to a single point of infinite density-a black hole or due to the merging of neutron stars, resulting in the creation of a singularity-a point of infinite density at the core of a black hole. This singularity has an incredibly high density, effectively packing a huge amount of mass into a tiny space. According to Einstein's theory of general relativity, mass warps space-time, causing objects to be attracted towards it. In the case of a black hole, the immense mass of the singularity creates an intense gravitational field that bends space-time extremely, resulting in immensely strong gravitational forces around the black hole. The black hole is surrounded by the event horizon which is the boundary of the black hole. This boundary delineates the point of no return for any object venturing too close, leading an object on an irreversible and continuous trajectory towards the singularity. Within black holes, the gravitational forces are exceptionally strong due to the intense curvature of space-time. Despite their invisibility, black holes exert a profound influence on their surroundings, distorting space-time, emitting radiation, and affecting the motion of nearby objects.

What Happens to a Wave near a black hole?

When a wave is travelling towards a black hole

When a wave travels towards a black hole, the wave gets bent due to the curvature of space-time. In a flat space, a wave follows a linear trajectory, but in curved space, its trajectory is altered and its path is bent. When a wave encounters a black hole, it can either bend but still move away from it towards infinity or cross the event horizon. If the wave crosses the event horizon the wave cannot escape and becomes trapped inside the black hole, the wave cannot escape because the gravitational force is now extremely strong and intensifies, due to the singularity—a point of infinite density. The severe curvature of space-time near the singularity acts like a gravitational funnel, compelling the wave to follow a trajectory inexorably to the point of infinite density, creating an inescapable path leading towards the singularity. For example an electromagnetic wave like visible light, that can be seen by the human eye, becomes effectively invisible once inside a black hole.This invisibility renders black holes black in colour, as they absorb all forms of electromagnetic radiation, without reflecting or emitting any light themselves. As these high-energy electromagnetic waves move into the intense gravitational field of a black hole, they experience significant distortion and curvature of space-time, making them undetectable from an external observer's perspective.

When a wave travels away from a black hole

when a wave travels close to the event horizon of a black hole and then travels away from it, the wave gets red-shifted. The extent of wavelength change depends on the strength of the curved space-time near a black hole. For instance, as visible light from a distant source nears a black hole, the intense gravitational field causes a shift towards longer wavelengths, transforming the light from the visible spectrum into the infrared range. A red shift occurs because, when a wave moves away from a black hole it has to move through a significantly more curved space-time in comparison to the region far away from the black hole, so when a wave does travel away from the black hole the wave loses energy.

By considering the energy and frequency of a photon of a wave near a black hole. The energy (E) of a photon is related to its frequency (f) by the formula $E = hf$, where (h) is Planck's constant. According to the equation energy loss results in the energy (E) of the photon to decrease resulting in the frequency decreasing. This change in frequency is linked to wavelength through the equation $c = fW$, where (c) is the speed of light and (W) is the wavelength. Therefore as frequency decreases wavelength increases resulting in a red shift.

Conclusion

In conclusion, when waves get close to black holes, they show us some really interesting things about how space works. As waves approach a black hole, they change their path a lot because of the way space bends around it. There are two main things that can happen: either the wave gets pulled into the black hole and can't escape, or it bends and manages to get away, but it looks different because of the strong gravity. This change is called a red shift, showing that the wave lost energy because of the black hole's pull. Understanding these phenomena not only enhances our comprehension of black holes but also their impact on the structure of the universe. By probing the behaviour of waves near black holes, we gain invaluable insights into the workings of gravity and spacetime.

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