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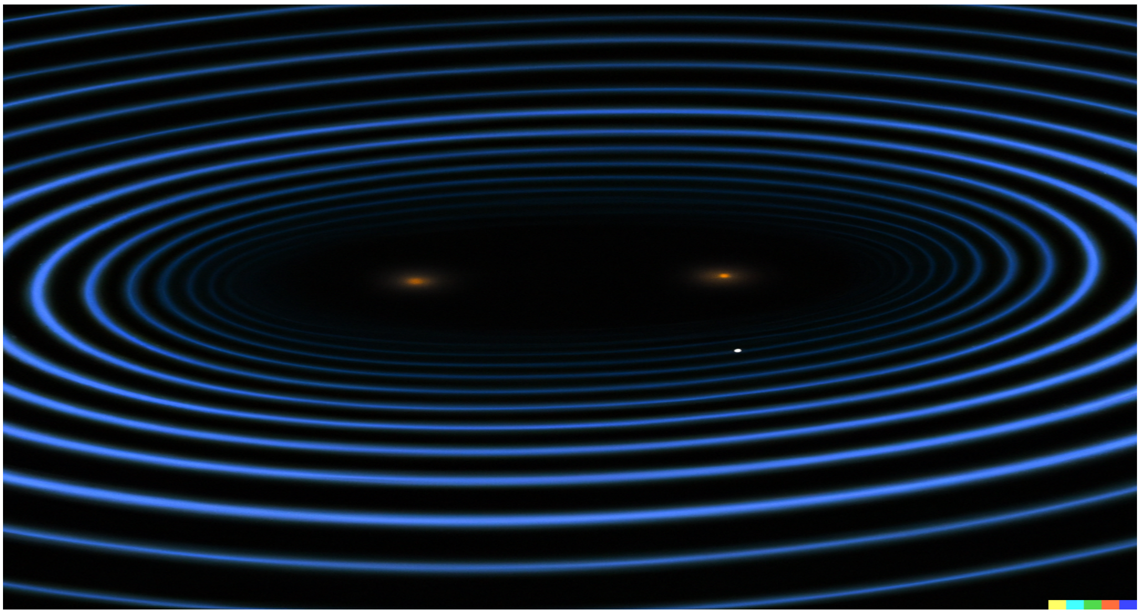
Ripples in Space-Time: Demystifying Gravitational Waves



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Abstract

This paper presents the development of an educational exhibit for the visitor gallery of the ETPathfinder, a crucial precursor project to the future Einstein Telescope (ET). The exhibits aim to demystify gravitational waves and engage non-scientific audiences, including children and dignitaries, by providing an accessible and immersive experience. The exhibits address the importance of public support and communication in scientific projects, drawing lessons from the cancellation of the Superconducting Super Collider. Furthermore, the strategic positioning of the region through the ETPathfinder is discussed, highlighting the short-term benefits of accelerated research, network expansion, and innovation. The exhibits also play a pivotal role in strengthening cooperation among various stakeholders in the region, showcasing the availability of expertise and the willingness to collaborate for the ET. Overall, this project underscores the significance of effective public engagement and collaboration in fostering scientific literacy, securing support for major scientific endeavors, and maximizing the potential of the ET for scientific, economic, and societal advancements.

Keywords— *Education and Outreach, ETPathfinder, Einstein Telescope (ET), Gravitational Waves, Non-scientific audiences, Public engagement*

1 Introduction

The Einstein Telescope, from hereon referred to as the ET, will be a third generation gravitational wave detector. A new generation of gravitational wave detectors is required to further advance science, since it is expected to allow measurement of stoichastic background waves. The location of this detector is currently to be decided between the Netherlands (in the South of Limburg) and Italy (on the Tyrrhenian island). Both of which have invested a significant amount of money into the project [1, 2].

The Netherlands has strengthened itself as a candidate by building the ETpathfinder, a research and development facility that develops the technologies needed for the Einstein Telescope. The ETpathfinder consistently attracts international scientists and facilitates collaboration between countries, even before the ET's final destination is decided [1].

A key role of the ETpathfinder is to coordinate stakeholders across the region, creating a conducive environment to collaboration and cooperation. Having a cooperative effort between countries and knowledge domains strengthens the regional consortium for the Einstein Telescope (ET), particularly when companies show strong interest and there is a well-established working relationship between countries [1].

However, whilst science as a whole is often regarded as purely an objective pursuit of knowledge and inquiry, more often than not the advancements of scientific projects and especially large scale projects inherently have political aspects [3]. The construction of scientific facilities requires a significant commitment of resources including funding, technical knowledge, and public backing. As a result, political dynamics, governmental policies, public opinion, and stakeholder interests invariably influence decision-making and the execution of major projects. The future of pioneering scientific undertakings is frequently decided within this intersection of scientific ambition and political realities.

One notable example and cautionary tale which highlights the importance of public perception and political will in shaping scientific journeys, is the Superconducting Super Collider's cancellation in the 1990s. Insufficient communication and outreach efforts led to significant opposition and public skepticism about the SSC, a particle accelerator of unprecedented magnitude. Eventually, in the absence of support, the project ultimately failed, resulting in missed opportunities for groundbreaking discoveries in particle physics [4].

Hence, it becomes imperative to examine science communication related to gravitational waves, especially aimed at students and politicians. A great deal of public support and understanding of science can be achieved through effective science communication. Since students represent the future generation of scientists and policymakers, it is crucial to communicate the significance and potential impact of gravitational wave research. Moreover, engaging politicians in science communication initiatives is essential to ensuring the ET receives continued funding and support.

The research question guiding this paper will therefore be: How can communication of gravitational waves be optimized to effectively engage and educate students and politicians, fostering their understanding, support, and enthusiasm for projects like the Einstein Telescope?

2 Background

In this section an overview of the most important background information pertaining to gravitational waves is presented.

First it is relevant to discuss further why detection of gravitational waves (GWs) is important to our understanding of the universe. To summarize, gravitational waves allow us to identify the location and types of relatively rare cosmological objects and may provide a more nuanced insight into the physics of the early universe [5]. Furthermore, they help us confirm or disprove different predictions made by Einsteins theory of relativity or explore its limitations.

Prior to recombination, estimated to have occurred at around 380,000 years after the Big Bang, the universe contained a dense, hot, primordial plasma consisting of free photons and ioninized atoms [6]. Free electrons and protons scatter photons, in a process known as Thompson Scattering, effectively making the plasma opaque to electromagnetic radiation [6, 7].

As the universe expanded and cooled down, eventually the protons and electrons combined into neutral hydrogen in a process now known as recombination [5, 7]. It was not until this point in time that the photons could travel freely without being scattered. This event produced the Cosmic Microwave Background, consisting of the photons which were released at this point in time [6, 8].

This means that using only light, we should not expect to gain insight into any events which preceded recombination. However, since GW couple to mass and energy instead of to electric charge and mass is a much weaker source of gravity than charge is to electromagnetism, they are not affected by Thompson scattering, they could freely travel [8]. As such, GW can be used to look back further in time than with light [9].

Such "primordial" gravitational waves are thought to have been produced as a direct result of the rapid expansion of the universe during inflation. However, such signals are incredibly difficult to detect, as they are buried under numerous sources of noise which are discussed in the following section [5, 8].

2.1 Sources and Creation

Whilst in some way GWs have properties comparable to other waves such as electro-magnetic waves like wavelength, frequency or the concept of polarization. In many other ways they differ, especially the conditions required for the production of any considerable amount of radiation. Electromagnetic waves are produced by indi
however rather than travelling through space-time, they are perturbations of spacetime itself. Therefore in principle any massive object can curve spacetime and generate gravitational waves, however they are much too weak in energy and amplitude to be quantified. Producing GWs within a detectable range requires supermassive objects, with enough energy to curve spacetime significantly. There are few of these sources massive enough to do this, predicted to exist first, and recently detected and confirmed by laser interferometers. The easiest sources to detect are binary systems of highly massive objects. For example, a black hole binary system, or neutron star and black hole, or supermassive black hole and black hole. These objects have enough energy to curve spacetime to a degree that emits substantial GWs, increasing in amplitude the closer the objects are to each other [10].

A potential additional source of GWs would be core collapse in massive stars. Such events give rise to supernovae, such events are expected to generate GWs if the collapse is not perfectly symmetric. Only in such a case, the moment of inertia is different along different axes, changing as the star rotates and deforms. In other words, for asymmetric core collapses the mass distribution of the star has a time-varying quadruple moment. Such time-varying quadruple moments are sources of gravitational radiation. However, as even a small perturbation breaks this symmetry, most of the core collapses are expected to be asymmetric in nature.

2.2 Propagation Through Space

Once emitted, the theory of general relativity posits that GW's travel with the speed of light, and manifest in the form of stretching and compressing the distances between points in space. However, as with other waves, they lose their amplitude as they travel due to dispersion. The magnitude of this effect is proportional to the inverse of the distance traveled. If a GWs travels twice the distance as an identical one, it will have one half the amplitude. Thus the longer the GWs has been traveling, the difficulty of detection will increase. It follows then that GWs from before recombination (Primordial GWs) have been traveling the longest and therefore will be the hardest to detect. [10].

Furthermore, as the universe expands, the wavelength of such gravitational waves is stretched and their amplitude decreased.

2.3 Detection

In general, a GWs can have a wide range of amplitudes, which can also be described by a measure called strain. Strain is the change in distance between any two points due to a GW. A common expected strain of GWs passing through earth is around 10^{-20}m. This means the change in distance is orders of magnitude smaller than an atom. Therefore physical distance would be not feasible as a measuring tool. From this, a different measurement is posed, waves. Using an interferometer, changes in phase of two separate laser sources can be measured, due to constructive or destructive interference. This process can be made sensitive enough to detect the small change in distance a GW provides [10]. Possessing the lowest amplitude or strain of all sources, primordial GW will be the hardest to detect and therefore require the most sensitive equipment.

It is expected that if primordial gravitational waves can indeed be measured that The ET will possess the technological capabilities to detect them [5].

3 Materials

3.1 Demonstration 1: Light in the Early universe

In order to foster an intuition for the phenomenon of light not being able to freely travel under early universe conditions an analogous situation was used and illustrated by a sand art toy (Figure 1). Such a toy consists of a transparent container filled with coloured sand, representing neutral hydrogen atoms, and some form of liquid. By agitating the container, the 'atoms' were mimicked to be randomly distributed and collided with each other, creating a dense and opaque medium such that when flashlight/led was placed behind the container it could be demonstrated that the light propagation would be impeded.

Figure 1: Sand art toy used to demonstrate opacity of the universe

3.2 Demonstration 2: Gravitational Wave Sources

Blender [11] was used to design and render three animations showcasing three unique sources of GWs. In addition, an app called (name of app) converted these animations into a specific video format. Finally, three mirror prisms, or hologram projectors were purchased, in order to use (app) and display the three animations as 3-dimensional holograms. Three black boxes were also used to place the hologram within, in order to give a darker setting and therefore a more visible image.

3.3 Demonstration 3: Propagation of Gravitational waves

In order to demonstrate

3.4 Demonstration 4: Detection of gravitational waves

The set-up for this demonstration followed closely the one presented in Kraus and Zahn [12].
A scaled model interferometer was built by replacing a laser source producing ultrasonic waves of 28 kHz. The reflective mirrors were then replaced by wooden plates. The typical half mirror (beam splitter) was adjusted for ultrasonic waves by means of a plastic wrap suspended in an embroidery loop. In this manner, the tightness of the plastic wrap changed to maximise the quality of the reflection and passing of the ultrasound waves.

The ultrasound was emmited by a transducer (transerciever SE04B25T, acquired from Gotron) which was connected to an Arduino UNO micro-controller. In order to receive the signal resulting from the interference, another identical transducer was used.

To visualize the signal, the second transducer was connected to a digital oscilloscope (QUIMAT TFT 2,4) which plotted the amplitude of the wave in real time. The circuit diagram is depicted in Figure 2. A number of 3D printed cogs (add total gear ratio) and a straight bar of corresponding cog teeth were utilised to allow for the movement of one of the mirrors by very small increments.

By emitting the ultrasound and slowly moving the mirror the two waves of sound were moved out of phase as their distance of propagation changed. The received signal, visible on the oscilloscope, varied from largest amplitude during constructive interference to the smallest amplitude during destructive interference. This effect replicated the stretching that a gravitational wave would produce in spacetime and hence the signal that a gravitational wave detector such as the Einstein Telescope(ET) could pick up.

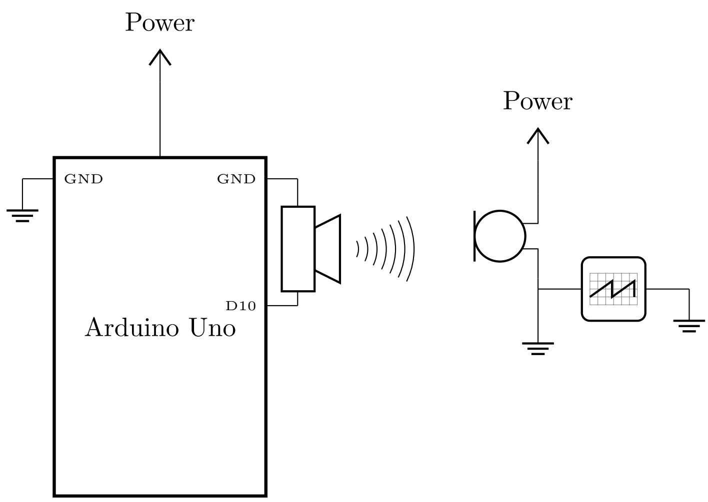

Figure 2: Circuit diagram. One of the ultrasonic transducers (here represented as a speaker) is connected to the digital pin of the Arduino. The other one is used as receiver (represented as a microphone) and connected to the oscilloscope

4 Results

	Problem	**Solution**	**Demonstration**	**Next Problem**
Light in the early Universe	We want to study the early universe but we can only detect emitted light emitted from 380,000 years after the big bang.	Unlike Electromagnetic waves, GW remain largely unaffected by physical matter and will travel relatively unobstructed.	Demonstration 1	But we haven't (yet) measured primordial GW but where do the GW that we **have** measured come from?
Sources of GW	Where do GW come from? How are they created? What are their sources?	Compact binaries (BNS, BBH, NSBH), neutron stars.	Demonstration 2	Once these GW reach us how can we detect them? escpecially since they lose so much energy before reaching us?
GW Propagation	How do Gravitational waves propagate	Properties of GW such as low interaction, energy loss, the speed at which they travel.	Demonstration 3	If the waves that arrive here carry such little energy, how do we measure them??
Detection?	How do the GW detectors allow us to measure low amplitude GW?	Explain how detectors work	Demonstration 4	Why do we need bigger detectors?

Table 1: Chronology of the different topics

5 Discussion

5.1 Demonstration 1

An unexpected benefit was that the voids or bubbles created by tilting the container, could serve as an analogy of the ionization of neutral hydrogen atoms by the first stars and galaxies, creating the first regions of transparancy in the early universe.

5.2 Demonstration 4

One of the main advantages of the ultrasonic interferometer is that it does not involve lasers, making it safe to be used by visitors of all ages (including children). In addition, it is built with cheap materials and therefore can be easily repaired in case of damage. The use of ultrasounds eliminate the problem of background noise interfering with the system.

6 Conclusion

Acknowlegements

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A Contributions

Name	**Contributions to the paper/presentation**	**Contributions to the exhibit**
Alexander Verheyden	•	• Design Posters
David Tóth	•	• Animations • Hologram Demonstration
Eli Showalter-Loch	• Background section (section 2)	• Light in the Early universe demonstration. • Instructions Demonstrations.
Eva Taliadorou	•	• Design posters
Finn Stapley	•	• Interferometer demonstration
Jens Hieronymus	•	• Student Leader • Interferometer demonstration
Nathalie Sowden	•	• Design posters • Website design
Sanne Aarts	• Introduction section (section 1). • Background section. • Formatting paper.	• Student Leader • Animations Gw production. • Gravity well demonstration.
Tom Chalabi Prat	•	• Interferometer demonstration
Tommaso Siligardi	•	• Interferometer demonstration
Zilan Mamuk	•	•

Table 2: Contribution of individuals to the final product

B Arduino code

```
int sender=10;
void setup() {
  pinMode(sender,[2]OUTPUT);

}

void loop() {
  tone(sender,2500);

}
```