GRAVITATIONAL WAVES RESEARCH AT TOROS UTRGV

PAMELA IVONNE LARA

Master's Program in Physics

PREVIEW

APPROVED:

Jorge A. López, Ph.D., Chair

Mario Diaz, Ph.D, Co-Chair

Marian Manciu, Ph.D.

Charles Ambler, Ph.D.
Dean of the Graduate School

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2018

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DEDICATION

I dedicate this thesis to my parents, Rene and Gladys Lara, and to Nathaniel Cowsert, my beloved nephew who left us too soon.

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PAMELA IVONNE LARA, B.S.

THESIS

Presented to the Faculty of the Graduate School of

The University of Texas at El Paso

in Partial Fulfillment

of the Requirements

for the Degree of

MASTER OF SCIENCE

Department of Physics

THE UNIVERSITY OF TEXAS AT EL PASO

August 2018

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ACKNOWLEDGEMENTS

I am deeply indebted to my advisor, Dr. Jorge A. Lopez for his guidance and support throughout my time at UTEP.

I also thank profusely my secondary advisor, Dr. Mario Diaz from UTRGV, for accepting me into TOROS at UTRGV.

I also acknowledge support from my TOROS UTRGV teammates, Dr. Martin Beroiz, Richard Camuccio, Moises Castillo, and Juan Garcia; I thank all of them for welcoming me into the team and for the Python lessons.

Finally, I thank UTEP for a hell of a ride.

PREVIEW

ABSTRACT

The detection of gravitational waves (GW) has directly opened a new era in the observation of cosmic events. One hundred years after its theoretical prediction we find ourselves immerged in the multi-messenger study of the signals at the root of gravitational wave detection. The electromagnetic (EM) counterpart to GW is the optical portion of that signal and the main objective in the organization of TOROS Collaboration: finding and studying kilonovas, the name given by Metzger (Metzger et al, 2010), to the EM counterpart to gravitational waves.

In order for TOROS to find kilonovas, it needed to create a python language pipeline. One of the steps of the pipeline was the design of an image calibration method script, also written in python language: Imageredux. In this thesis the author gives an account of her part on the design of such script and its application to the field of HAT-P-27 (images captured on the night of June 22, 2017), as a test subject. Also, and account of TOROS Collaboration detection of the kilonova SSS17a found as a counterpart to GW170817 is given.

PREVIEW

TABLE OF CONTENTS

PREVIEW

LIST OF FIGURES

PREVIEW

PREVIEW

CHAPTER 1: INTRODUCTION

Gravitational waves are vibrations in space-time, the material from which the universe is made. In 1916, Albert Einstein recognized that, according to his General Theory of Relativity, the most violent bodies of the cosmos release part of their mass in the form of energy through these waves. He determined that the solutions of the linearized equations to weak field are transverse waves moving at the speed of light (Manreza, 2017). For many years it was thought that these space-time waves were just a theoretical result and they were never going to be able to be detected. However, on September 14 of the year 2015 the first direct detection of a gravitational wave was made.

In general, a wave is an oscillation that transports energy. The waves can be mechanical if the oscillation propagates in a medium, or electromagnetic if they are oscillations of electric and magnetic fields due to the accelerated movement of electric charges. In particular, gravitational waves are produced by accelerated movement of masses, which cause fluctuations in the curvature of space-time, that is, they are periodic deformations of space-time that affect the relative distances between points of space. Gravitational waves are obtained as solutions of Einstein's equations

PREVIEW

$$G_{\mu\nu} = kT_{\mu\nu} \tag{1}$$

where the left side is the Einstein tensor, which is a derivative function of the metric tensor ($g_{\mu\nu}$), which describes the curvature of space-time. In the right side is the energy-momentum tensor, which describes the distribution of matter and $k = \frac{8\pi G}{c^4}$ is a constant dependent of the gravitational constant G and speed of the light c. In general, equations (1) are a set of ten non-linear equations partial derivatives, whit known solutions for some cases. To obtain gravitational waves Einstein made some approximations. First, he considered the solution of equations in the vacuum, that is, he took $T_{\mu\nu} = 0$, and ignored the non-linear effects, so that the metric could be written as $g_{\mu\nu} = \eta_{\mu\nu} + h_{\mu\nu,}$ being $\eta_{\mu\nu}$ the metric of the flat space and $h_{\mu\nu}$ a small disturbance to this space ($|h_{\mu\nu}| \ll 1$). Thus, equations (1) are reduced to

$$\Box h_{\mu\nu} = 0, \tag{2}$$

where $\Box = -\frac{\partial^2}{\partial t^2} + \nabla^2$ is D'Alembert operator. Equation (2) is a wave equation whose typical solution (in the case of a wave that travels in the z-direction), has the shape

$$h_{\mu\nu} = \begin{pmatrix} 0 & 0 & 0 & 0 \\ 0 & h_+ & h_x & 0 \\ 0 & h_x & h_+ & 0 \\ 0 & 0 & 0 & 0 \end{pmatrix} \tag{3}$$

PREVIEW

With $h_+ \, and \, h_x$ the only non-zero components that correspond to the possible polarizations ($+ \; y \; \times$) of the wave, respectively. The effect of the passage of this wave on a ring of test masses is to contract and expand the distances in directions orthogonal, as shown in Figure 1.2. Therefore, we can characterize gravitational waves as waves traveling at the speed of light with two polarizations and whose amplitude is determined by the magnitude dimensionless $h = 2\frac{\Delta L}{L}$ where L is the length between two test masses and ΔL are the variations of that length. Unlike electromagnetic waves, for which the dominant term in the emission comes from the dipolar moment, for the gravitational waves the dipole moment is zero (a consequence of there being no negative and positive masses), which is why the quadrupole term dominates. In this way the amplitude of gravitational waves is proportional to the second derivative of the quadrupole of mass of the source. This implies that there are no distributions of spherically symmetrical matter that emit gravitational waves (Saulson, 1994).

While all the accelerated movements of asymmetric mass emit gravitational waves, being the gravitational interaction very weak, there is the need for large masses performing very fast movements to generate disturbances in the space-time for them to be measurable. This means that the main sources of gravitational waves (Manreza, 2017), with potential to be detectable are:

- Binary systems of black holes, neutron stars, or a combination of both: as the orbital radius of the binary system decreases as both compact objects approach, gravitational waves are emitted.
- Explosions of stars in the form of Supernovas: if the explosion is asymmetric, large amounts of matter are ejected at high speeds, which produces gravitational radiation.
- Rotating neutron stars: although in general the rotating neutron stars are objects spherically symmetrical, in some cases the star may be deformed and therefore emits gravitational radiation.
- Inflation: many cosmological models postulate that at very early stages of the evolution of the universe, this expanded in an accelerated way. If the expansion was asymmetrical, it could have emitted gravitational waves.

PREVIEW

1.1 BRIEF HISTORY OF GRAVITATIONAL WAVES DETECTION

A background history on the topic needs to start with the French mathematician Henri Poincaré who, on July 5 of 1905, published "Sur la Dynamique d' l'electron" (On the dynamics of electrons), and where he presented his thoughts about relativity. On this paper, Poincaré suggested that "gravity was transmitted through a gravitational wave" (Cervantes-Cota, 2015). A decade later Einstein's General Theory of Relativity was published.

For Einstein, gravity was not a force of attraction between object, a Newtonian postulate, but a distortion in the fabric of space and time; as one of his later collaborators nicely put it *"Spacetime tells matter how to move; matter tells spacetime how to curve." (*Wheeler*, 2000)*. Because Einstein himself was not very assured that gravitational waves could be detected and because of the amount of polemic awakened by the subject, he continued working, either to prove their existence or to finally declare that they were not plausible. During the 1930s, Einstein and Nathan Rosen, one of his collaborators, revealed a gravitational wave solution that did not correspond to a physically possible situation.

On June 1, 1936, Einstein and Rosen presented the paper (to the journal Physical Review), *Are There Gravitational Waves?*, however, they later withdrew it (Daniel, 2005). Suddenly it appeared that gravitational waves did not exist. Corresponding with his friend Max Born, Einstein wrote "Together with a young collaborator, I arrive at the interesting result that gravitational waves do not exist, though they have been a certainty to the first approximation" (Born-Einstein, 2005). Finding calculation errors in his work with Rosen, Einstein made the needed corrections to the galley proof and rewrote his paper under the title *On Gravitational*

PREVIEW

Waves (Daniel, 2005), and kept his beliefs on the existence of gravitational waves (Cervantes-Cota, 2015).

Putting it in fundamental terms, the problem was in the coordinate system chosen by Einstein. A contemporary of his, the young British theoretical physicist Felix A. E. Pirani solved this problem. In 1956 Pirani published the article titled *On the Physical Significance of the Riemann tensor* (Pirani, 1956). In his paper, Pirani "settled on the notion that an observable effect of a passing gravitational wave is the undulating separation between two test masses in space (something gravitational physicists called "geodesic deviation" or "tidal deviation")" (Larson, 2016).

A milestone in relativity-gravitational wave's duo can be found in the 1957 Chapel Hill Conferences. After 19 months after the passing of Albert Einstein, 44 scientists met in North

Caroline for this critical conference. At this point, all physicist agreed on the fundamental need to show the effects that any gravitational phenomena would have in nature. One of the topics

PREVIEW

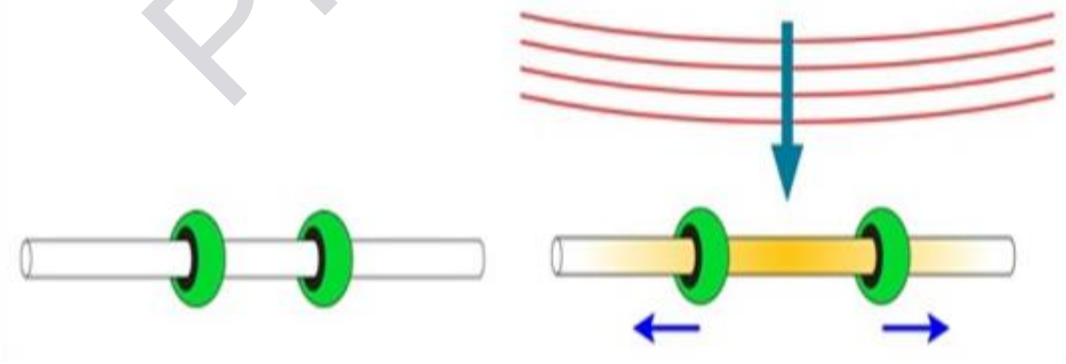

Figure 1.1: Sticky bead argument illustration

discussed there was whether or not a gravitational wave would carry energy. Among the attendees was Richard Feynman. Feynman expanded on Pirani's idea with his thought experiment "sticky bead argument." He imagined two freely-moving beads connected to a rod as shown in figure 1.1 (Chaudhuri, 2017). When the direction of wave propagation is perpendicular to the direction of the rod, the tidal wave generated (the longitudinal stresses, namely alternative compressions and extensions), will produce the motion of the beads relative to the stick. In the presence of friction, this relative motion will result in the production of heat (Chaudhuri, 2017). ‘I think it is easy to see that if gravitational waves can be created, they can carry energy and can do work" (DeWitt, 2011). This heating due to friction represents the transmitted energy from the gravitational wave to the bar. When Feynman arguments were added to the arguments of other participants, a general consent was reached about the existence of gravitational waves.

PREVIEW

A later point of discussion was about measuring the masses’ displacement produced by the traveling wave. How can we measure the length of the displacement if any measuring tool we use would also be affected by the wave? Would be like trying to measure a distance using a rubber band. Years later this was solved by measuring, instead, the time taken by the light to travel the displaced distance since the speed of light is constant and unperturbed by the gravitational wave (Chaudhuri, 2017).

1.2 GRAVITATIONAL WAVES DETECTION METHODS

The first attempts to detect gravitational waves came from another 1957 Chapel Hill Conference attendee, the American physicist Joseph Weber. Weber decided to build a contraption capable of detecting gravitational radiation. After much research, he opted for a cylindrical bar, an antenna like resonance-mass detector of 2m in length by 0.5m in diameter made of aluminum, and monitored by piezoelectric transducers. Based on the knowledge that any solid has a natural oscillation frequency (mainly depending on the solid's size), if the bar was to be perturbed (by a small bump for example), it would respond with an oscillation, that would reach its maximum when the perturbation is attuned to the natural frequency of oscillation of the instrument. If a gravitational wave, with the same oscillation frequency as of the cylinder, traveled through the bar, this would vibrate with a quantifiable amplitude.

Figure 1.2 illustrates this effect on a ring of particles which is the foundation for resonant-mass gravitational wave detectors. The cylindrical bars would oscillate longitudinally as a gravitational wave travels through them and in a frequency resonant with the wave (Magalhães, 2005). Joseph Weber hoped to be able to measure these vibrations. Little did he know this was an impossible task for his experimental settings since the magnitude of the amplitude turned out to be of the order of 10^{-21}m (Saulson, 1994).

The significant limitations Weber encountered were the background noise (seismic waves for example), and not knowing the order of frequency of the gravitational waves. To attack these problems he built several cylinders of different sizes hoping to match that of the waves. In 1969 he reported that a couple of his bars had detected similar signals, "Six detectors have been operating. Four of them are aluminum cylinders of 153-cm length tuned to a narrow band of frequencies ($\Delta\omega = 0.1\, rad\ sec^{-1}$) near 1660 Hz. The bandwidth is adjustable. Piezoelectric

PREVIEW

crystals bonded to their surfaces couple the normal-mode oscillations to an electromagnetic degree of freedom." (Weber, 1969). His results inspired other scientists to recreate his experiment.

After several of these efforts failed to produce acceptable results, the scientific community despaired in their hopes to confirm Einstein's predictions. Then in 1974 came the work of Hulse and Taylor (Hulse and Taylor, 1975). Theirs was not a direct detection but a confirmation of the existence of gravitational waves. For decades, they studied the pulses we receive from PSR B1913+163, a neutron star in a binary neutron star (BNS) system. The slow rate of period decrease of the pulses for this pulsar matched precisely the rate at which they were losing energy in gravitational waves, as predicted by General Relativity.

PREVIEW

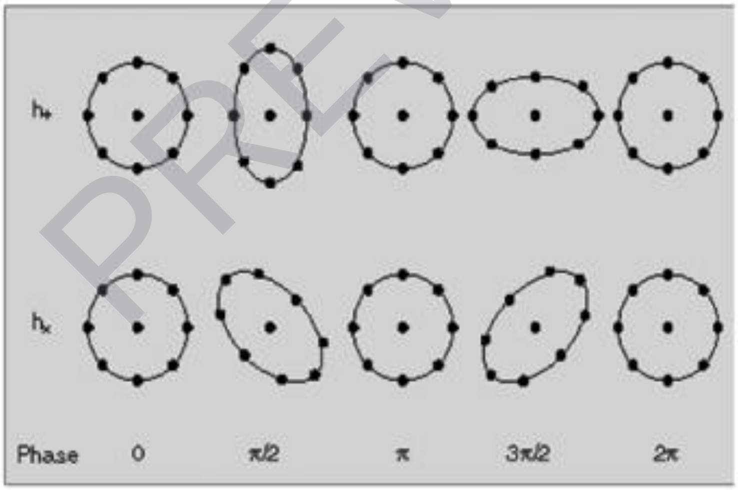

Figure 1.2: Resonance-mass detector effect on stationary particles. When a gravitational wave passes through a ring of particles, it changes their position depending on the wave's polarization. Top line, wave with polarization "+". Bottom line, wave with polarization "×".

The discovery and analysis awarded them the 1993 Nobel Prize in Physics "for the discovery of a new type of pulsar, a discovery that has opened up new possibilities for the study