Gravitational Waves: A Brief and Lyrical Introduction

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Preface

This document takes a different tack towards communicating science to a non-technical audience. It does so by first presenting a new, creative writing by the author related to gravitational waves. The themes of the writing are subsequently elucidated in a pedagogical text following it. The level of detail provided in the explanatory text is intended to be sufficient for a non-expert to understand the main ideas in the verse. It is not intended to be an exhaustive summary of gravitational waves. Instead, there are references to technical articles and non-technical books where interested readers can pursue the subjects in greater detail.

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A Second Birth

Turning and turning in a *narrowing* gyre,
Where silence and darkness pervade,
These things will combine.
Screeching like an cosmic falcon,
Its chirp pierces across space and time,
Because its call is built of space and time.
This stirring is unstable, but not anarchic;
Its pitch evolves with mathematical certainty
As these objects twist towards a center.
This dance begins as a dirge,
Rises over astronomical times to a minuet, and
Peaks with passionate intensity as a scherzo.

What is the resolution to this increased haste?
Is some revelation at hand?
There will be no visions of a chimera
With a lion's body and man's head,
But a unity, with two becoming one and the same.
The coda to this fury, is more darkness and silence.
Like a struck bell, the once shrill tone fades
Leaving space and time static and enduring
Until it finds its next partner in song and dance.
Eons of quiescence may one day be shattered
By the violent rocking space and time
As this massive beast swirls anew to be born again.

Introduction

The work on the previous page is inspired by William Butler Yeats' famous lyrical poem "The Second Coming" (see, e.g., [1]). Whereas Yeats' work is often understood as a depiction of Europe following the first World War in terms Yeats' historical theory of different epochs (the gyres) using common Christian iconography, the adaptation above is centered around the merger of two black holes and the gravitational waves emitted during this process. The remainder of this article will begin with a brief historical overview of the theoretical prediction of gravitational waves, and the long process that led to their discovery one-hundred years later. It will then describe the gravitational waves emitted during the merger of two black holes, which is the main subject of the poem. The relationship between the poem and the relevant physics will be explained in this part.

Background on Gravitational Waves

The Theory of General Relativity

Einstein published his theory of general relativity in the year 1915 [2], following a decade-long effort to formulate a theory of gravitation following his 1905 paper on the theory of special relativity [3] (Einstein's *Autobiographical Notes* has some discussion of this process [4]). A key aspect of both special and general relativity is that points in three-dimensional space and moments in time are not treated separately, but they are joined together in a four-dimensional spacetime. In this construct, time is represented through the distance that light travels in a given interval of time, so that space and time are treated together, on an equal footing, as types of distances in a four-dimensional spacetime continuum. Spacetime can be curved, and in Einstein's theory of general relativity, the density of energy and momentum, as well as pressure and shearing stress of material objects ("stress-energy" for short), are responsible for the curving of spacetime. The spacetime metric is used to measure distances between nearby points in spacetime, which serves as a generalization of the more familiar Pythagorean distance in ordinary flat space.

Einstein's equations of general relativity are mathematical relations (specifically, partial differential equations) that relate derivatives of the ten independent components of the metric to the ten such components of the stress-energy of matter. These equations were of a sufficient complexity that Einstein was initially pessimistic that they could be solved in any cases of much physical utility. Remarkably, an exact solution was found within a year of Einstein's publication of the theory of general relativity by Karl Schwarzschild [5, 6], and the solution outside of matter was eventually understood to be a non-rotating black hole (see, e.g., [7] for a discussion in a similar style to this work, or [8] for a much more extensive discussion).

Theoretical Prediction of Gravitational Waves

Einstein took a different approach from Schwarzschild to finding solutions to the field equations of general relativity. Specifically, he looked for solutions where the material bodies curve spacetime very weakly, so that the field equations could be solved approximately. The resulting spacetime is approximately flat (almost like that in special relativity), but has a small amount of curvature generated by the relatively low energy densities of matter. Einstein's first paper on the subject was published in 1916 [9]. In this paper, he found that the equations of general relativity predicted that changes in the metric variable propagated at the speed of light in this approximation. The equations shared some similarities to those for the electric and magnetic field in electromagnetism, and Einstein interpreted these solutions as being gravitational waves. Unlike electromagnetic waves, however, gravitational waves are distortions of spacetime itself that propagate like waves.

There were some puzzling features of the gravitational waves that Einstein discussed in his 1916 paper: namely, in the coordinates used by Einstein all components of the metric propagated as waves at the speed of light, but only some of the metric components appeared to carry energy away from the system of matter which produced them, whereas others did not. Einstein came to a clearer understanding of these waves two years later in 1918 when he published a second paper on the subject [10]. Here Einstein explained in more detail why only two of the components of the waves were physical (the so-called "transverse traceless" parts), in the sense that they produce a loss of energy from the system. There was also a factor-of-two error in this latter calculation, which was later corrected by Eddington [11] in a paper in 1922. Eddington's 1922 paper confirmed that the transverse traceless waves of Einstein's 1918 paper propagate at the speed of light and are responsible for the energy losses, but the remaining components of the metric do not. This led Eddington to describe the coordinate-dependent waves discussed in Einstein's 1916 paper as coordinate artifacts that traveled at "the speed of thought" [11]. Eddington's paper also estimated the size of the energy losses from mechanical systems and binary stars. The rate of energy loss was exceedingly small, which made the prospects of verifying the existence of gravitational waves through observations seem unlikely.

Towards the Direct Detection of Gravitational Waves

Without a clear measurable or observable source of gravitational waves, the field was somewhat dormant for many decades after Einstein's and Eddington's works (though not without some controversies in some foundational aspects of the nature of gravitational waves; see, e.g., [12]). In the 1960s and '70s, however, there were experimental and observational developments that made the prospects for detecting gravitational waves seem much more promising.

On the experimental side, there were dramatic improvements in electronics, low-noise measurements, laser light sources, and computing power, to name just a few. Several of these improvements led the experimental physicist Joseph Weber to propose building gravitational-wave detectors [13]. Weber also claimed to have found observational evidence for the discovery of gravitational waves in the late 1960s [14], but these claims did not hold up under further scrutiny. The more promising method would prove to be using laser interferometers, which was a method proposed by Pustovoit and Gertsenshtein in 1962 [15], and was spelled out a decade later in more technical detail by Rainer Weiss [16]. Weiss's design would become the basis of the Laser Interferometer Gravitational-Wave Observatory (LIGO), which would detect gravitational waves over forty years later.

On the observational side, astrophysical compact objects, such as neutron stars and black holes were discovered. Both types of objects can form after a star more massive than the Sun undergoes a supernova and leaves a dense neutron-rich remnant (the neutron star) or the material compresses below the radius of the event horizon and forms a black hole. Neutron stars were discovered through the regular radio pulses that they emit [17]. The emission of x-rays from astrophysical sources was discovered earlier [18], but it was only later that these x-rays were identified as coming from a binary of a black hole and a second star, from which the black hole was accreting matter [19, 20]. Not only would the supernova explosions that form the neutron stars and black holes be a potential source of gravitational waves, but binaries formed from black holes and neutron stars would be generate gravitational waves that were orders of magnitude stronger than those estimated by Eddington in 1922. The small size of these objects would allow them to get much closer before colliding, and to reach significant fractions of the speed of light as they orbit each other; this made the prospects for detecting binaries of compact objects much more promising than those for ordinary stars.

One more key result was the discovery of a pulsar in a binary [21], which was published in 1975. Because of the remarkable accuracy with which pulses from the radio pulsar can be timed, after a few years of observation of this pulsar, the effects of the emission of gravitational waves were observed in the arrival time of the pulses. As energy was carried away from the binary, the orbital period decreased and the other orbital elements of the binary subtly changed. The evolution of the binary agreed precisely with the emission of gravitational waves, as predicted by general relativity, which led to an important observational confirmation of gravitational waves. The discoverers of this binary pulsar (Hulse and Taylor) were awarded the 1993 Nobel Prize in Physics for this work.

The Direct Detection of Gravitational Waves

The remarkable progress in experimental physics and observational astrophysics described above made the possibility of the direct detection of gravitational waves, though still an extremely challenging prospect, seem closer to the range of possibility. While some experimentalists were still pursuing detectors similar to those of Weber, in 1984 Weiss, Ronald Drever and Kip Thorne started the LIGO collaboration to use Weiss's interferometer design to detect gravitational waves. Prototype detectors were built at a one-hundredth scale (forty meters in length) at the home institutes of Weiss (MIT) and Drever and Thorne (Caltech). After a decade of research and development, the full-scale (four kilometer) detectors were approved for construction, with one built in Hanford, Washington and a second built in Livingston, Louisiana. Having two detectors allows for a greater degree of confidence in the detection of astrophysical gravitational-wave sources, as opposed to terrestrial phenomena that could mimic the gravitational waves. The decades-long process of building and commissioning the detectors began soon after the detectors were funded by the National Science Foundation. The advanced detectors began operating in late 2015, and as soon as they started their first observing run, they discovered a coincident signal in the two detectors that was consistent with the merger of two black holes. After months of careful scrutiny by the LIGO collaboration, and the Virgo collaboration (a third gravitational-wave detector in Italy), the collaborations determined with confidence that the signal they observed did arise from the collisions of two black holes. The importance of this discovery was realized immediately, and the 2017 Nobel Prize was awarded to Weiss, Thorne and Barry Barish for their work in founding and leading the LIGO collaboration.

Explanation of the Poem

The poem describes the process of two black holes merging. As two black holes orbit around each other, like the binary pulsars, the black holes emit gravitational waves. These gravitational waves carry away energy, and because the total interaction energy of the black holes and gravitational waves is conserved, this means that the potential energy of the black holes decreases. Because the gravitational interaction between the black holes is attractive, this makes the black holes orbit closer to each other, at a higher frequency. However, the faster motion of the black holes increases the amplitude of the gravitational waves, which increases the amount of energy lost, thereby leading to an unstable process. Because both the frequency and intensity of the waves increase in the process, it is referred to as a "chirp" signal during this inspiral. This is described in the first portion of the poem referring to the narrowing gyre, the chirp of this cosmic falcon, and the unstable stirring.

The rate at which the black holes inspiral, when they are more widely separated, however, is exceedingly slow. As an example, the binary pulsar discovered by Hulse and Taylor, where indirect evidence of gravitational waves were first observed, will continue to spiral around each other for another roughly three-hundred million years before the two neutron stars collide! This is useful to compare to the current orbital period of the two pulsars in the binary, which orbit around each other roughly once every eight hours. The extremely long time to inspiral is the astronomical times referred to at the end of the first stanza. LIGO and Virgo, however, can measure the last stages of this long inspiral, when the black holes are orbiting each other at least five times a second. At this late stage of the inspiral, the gravitational waves are so intense, that the two black holes will collide in a few seconds.

The resolution described in the second stanza describes the merger and ringdown stages of the process. As the two black holes approach a separation that is close to the size of the individual black holes' horizons, their orbital angular momentum about the center of mass of the binary is now too small to keep the black holes from merging. At this last stage, the two black holes plunge towards each other, the gravitational waves reach their peak, and the two black hole mutually engulf the other to form a single larger black hole. This is the unity (two becoming one) described in the poem. The single black hole starts in a highly distorted state, but these distortions in the curvature of spacetime rapidly are radiated away as gravitational waves. The black hole quickly settles into a quiescent state, rotating about an axis, and no longer produces gravitational waves. This last stage of gravitational-wave emission is called the ringdown, precisely because it resembles the damped oscillations of a bell.

The final lines of the poem reflect on what may happen to the black hole very far in the future. If the black hole resided in a part of a galaxy that was far from the core or other over-densities of stars, then it would likely continue its existence as a single isolated black hole, in the darkness and silence of space for the foreseeable future. However, if it resides in a more dynamic region of the galaxy, there is the chance that it could pair up with another star or compact object (like a second black hole) and repeat this inspiral and merger process again. Information about the spin magnitudes and directions of the black holes are conveyed in the gravitational waves. Analyzing their orientation with gravitational wave measurements could allow one to infer if the black holes in the binary had formed from interactions of this type, or even if one of the black holes had undergone a previous merger.

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