School of Physics and Astronomy

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Gravity Spy and X-Pypeline: A multidisciplinary approach to characterizing and understanding non-astrophysical gravitational wave data and its impact on searches for unmodelled signals

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Summary of thesis

With the first direct detection of gravitational waves, the Advanced Laser Interferometer Gravitational-wave Observatory (aLIGO) has initiated a new field of astronomy by providing an alternate means of sensing the Universe. The extreme sensitivity required to make such detections is achieved through exquisite isolation of all sensitive components of aLIGO from non-gravitational-wave disturbances. Nonetheless, aLIGO is still susceptible to a variety of instrumental and environmental sources of noise that contaminate the data. Of particular concern are noise features known as *glitches*, which are transient and non-Gaussian in their nature, and occur at a high enough rate that the possibility of accidental coincidence between the two aLIGO detectors is non-negligible. Glitches come in a wide range of time-frequency-amplitude morphologies, with new morphologies appearing as the detector evolves. Since they can obscure or mimic true gravitational-wave signals, a robust characterization of glitches is paramount in the effort to achieve the gravitational-wave detection rates that are allowed by the design sensitivity of aLIGO. For this reason, over the past few years, glitch classification techniques have been developed to help make this task easier. Specifically, I explore the effect of glitches, and their suppression, on key gravitational-wave searches such as that for a Galactic supernova. Moreover, I explore the impact of including machine learning techniques in the post-processing stage of the gravitational-wave search algorithm, "X-Pypeline". When performing a two detector network search for a gravitational wave from a Galactic supernova, this thesis finds that including information about glitch families and using machine learning techniques in the post-processing stages of the analysis can improve the sensitive range of the search by 10-15 percent over the standard post-processing method.

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Chapter 1

Introduction

Einstein's general theory of relativity (GR) predicts that all accelerating objects with non-symmetric mass distributions produce gravitational waves (GW), which are oscillations in the space-time metric [1]. In the same way as light, gravitational effects do not propagate with infinite speed. Whenever the distribution of mass in a given system changes (for example, when one drops a basketball), the gravitational field adapts to this new mass distribution. The speed at which this change propagates is equal to the speed of light, and the resulting changes in the curvature of space-time are GWs. GWs expand and contract space-time orthogonal to the direction of their motion. Therefore, an instrument designed to detect the displacement of two objects relative to each other could sense a gravitational wave passing through it. The problem, however, lies in the amplitude of GWs, and, consequently how much they displace objects. Even from the most dramatic birthplaces of GWs, the moments before, during and after the merger of two large compact binary objects such as binary black holes (BBH) and binary neutron stars (BNS), the amplitude of the resulting waves at cosmological distances from the event are on the order of 10^{-18} m when sensed by a 4 kilometer interferometer. For context, this displacement of space-time is 1000 times smaller than the nucleus of an atom.

Despite these challenges, GWs are detectable through the combined use of multiple instruments called interferometers. These Michelson interferometers with Fabry-Perot cavities utilize laser light that is sent to a beam splitter which causes half the light to go down each of two orthogonal arms. At the end of each of these arms is a reflective mirror. The beams reflect off these mirrors and recombine at the beam splitter, thereby sending a portion of the light toward a photodiode, and the remaining light back towards the laser. This photodiode outputs a current proportional to the average photon flux at the detector [2]. Any differential variation in the lengths of the arms will change the power seen at the photodetector. For example, if a GW passes through an interferometer perpendicular to its arms (i.e. incident from directly below or above it), the mirror of one arm will be expanded away from the photodiode as the other mirror is contracted towards the photodiode. As a result,

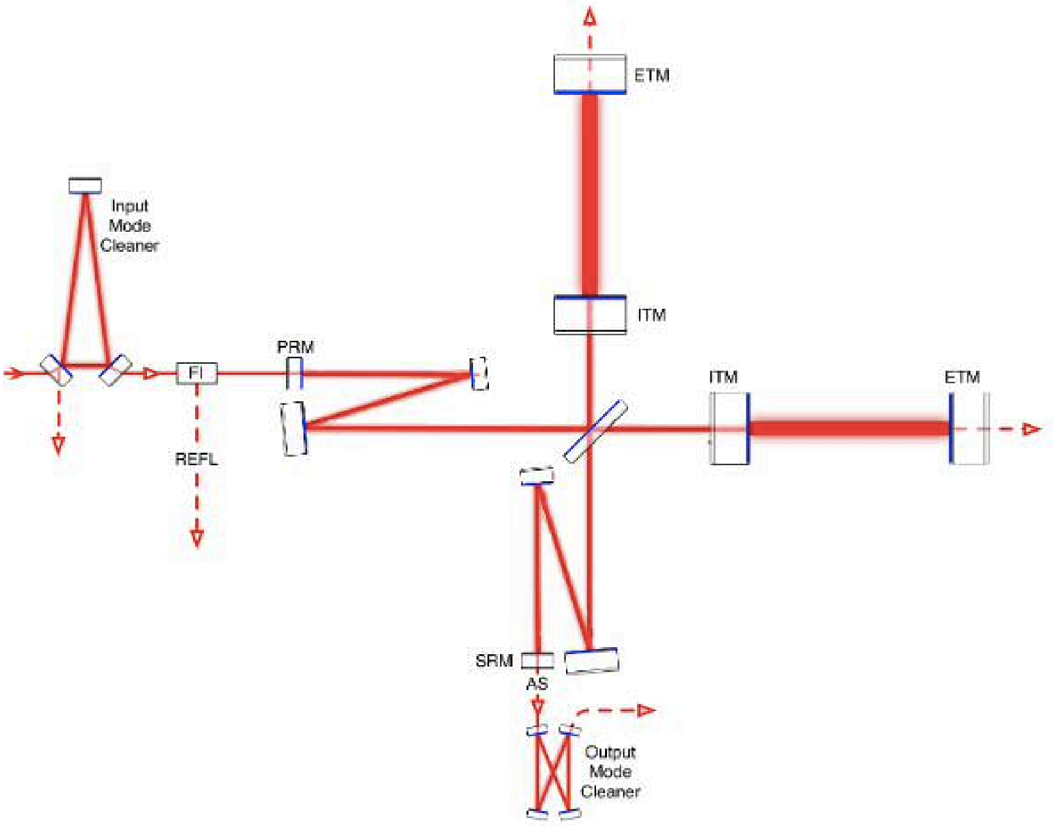

Figure 1.1: Illustration of the optical layout of Advanced Laser Interferometer Gravitational Wave Observatory [3].

the power seen at the photodiode modulates as the length of both arms change as a function of time. In this way, the length of the cavity affects the sensitivity of an interferometer as longer cavities yield larger phase delays between the light in the arms in the cavities.

Current ground-based detectors include the Advanced Laser Interferometer Gravitational Wave Observatory (aLIGO) [3], a diagram of which can be seen in 1.1, Advanced Virgo (AdVirgo) [4], and GEO600 [5]. Future ground-based detectors include KAGRA [6], which will be located in Japan, and LIGO India [7]. aLIGO consists of two 4 kilometer interferometers at Hanford, WA (H1) and Livingston, LA (L1) in the United States. Virgo consists of one 3 kilometer interferometer located in Pisa, Italy (V1). GEO consists of one 600 meter interferometer located in Hanover, Germany (G1). Despite the interferometers inherit abilities to sense the passing of a GW, many environmental (i.e. earthquakes, magnetic field, etc) and instrumental-sources of noise can move the mirrors of the interferometer or affect the light measured at the photo-diode in such a way as to either mimic or mask a GW. Therefore, great care has been taken to isolate the mirrors from as many known sources of transient non-gravitational wave noise, such as the addition of pendulums to reduce the motion of the mirrors and transducers which use seismometers to de-

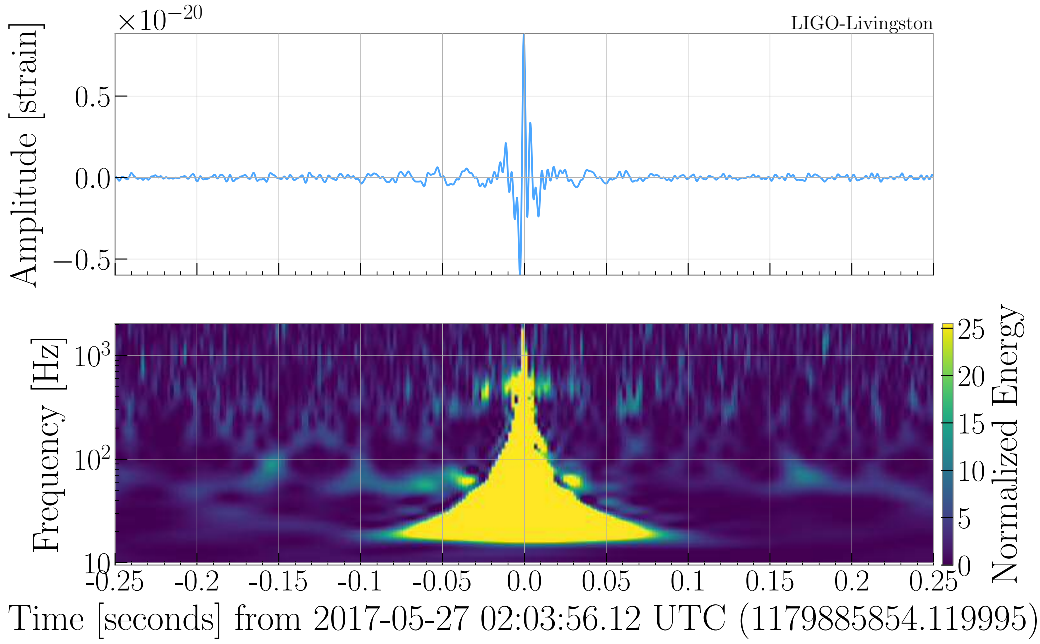

Figure 1.2: Example of an isolated Electrostatic Drive Overflow similar to that which occurred in the Livingston detector at the time of the BNS signal [13]. Top panel: Gravitational wave strain data that has been high and low pass filtered at frequencies of 50 and 290, respectively. Bottom panel: A special type of spectrogram that is made by performing a wavelet transformation on the timeseries data. The resulting image is referred to as a q-scan [14].

tect and counteract earthquakes. Starting in September 2015 and continuing to this day, the success of this work has been seen in the detection of GWs from compact binary coalescences of binary black holes [8–12] and binary neutron stars [13] by aLIGO and AdVirgo. These detections came while the aLIGO detectors collected data as part of their first observing run from September 2015 to January 2016 (O1) and second observing run from November 2016 to August 2017 (O2) and AdVirgo collected data between August 01, 2017 until August 25, 2017.

Despite these successes and efforts to isolate the interferometers from sources of transient non-gravitational wave noise, aLIGO and AdVirgo data is still contaminated with these transient artifacts. In the 51.5 days of O1 alone, approximately 10^6 glitches over a minimum signal-to-noise ratio (SNR) threshold of 6 were recorded [15]. Many of these noise features appear similar when viewed in a time-frequency space known as a spectrogram. Figure 1.2 shows the strain and spectrogram of one such excess noise occurrence at the Livingston detector that is similar to the noise feature seen in coincidence with the BNS detection [13]. Due to the sheer quantity of these excess noise features, however, the ability to comprehensively group or understand these morphological classes has been challenging for LIGO and Virgo scientists. Clean data is desirable for a number of reasons including, but not