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Skynet Astromancer Suite: Gravitymancer

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Abstract

The Gravitymancer processing tool within Skynet's Astromancer suite opens a unique window for students of introductory astronomy courses to explore the most powerful events observed in our Universe – the merger of binary neutron-star systems and black-hole systems. These merger events produce short-lived bursts of gravitational radiation, as observed by one or more of the following gravitational-wave observatories: LIGO, Virgo, and KAGRA. Students can use Gravitymancer to load and interpret the archival event data, finding useful properties like the total mass and mass ratio of the binary system, distance, and inclination angle. While on the surface, students can interpret gravitational-wave events with an easy-to-use GUI, we present here the complex processing utilized to make this tool work.

Keywords: Gravitational Waves, Undergraduate Labs

1 Revolutionizing Introductory Astronomy

The Skynet-based laboratory curriculum MWU! (Multi-Wavelength Universe!), supported by a $3*M* DoD education grant, has the goal of giving both astronomy and non-astronomy majors alike research-style experiences at the introductory level. In carrying out these experiences, often with professional instrumentation, they not only learn about the universe in a more personal way, but have authentic experiences that hopefully positively affect their outlook on pursuing STEM careers. Authentic experiences in STEM can help develop and maintain a science identity Mraz-Craig et al. (2018) while also maintaining an interest in STEM careers (Carlone and Johnson, 2007). Within the MWU! curriculum the authentic experiences involve collecting new data with remote telescopes, or using recently acquired professional data, and analyzing that data to refine the parameters of the phenomenon under study. In this way, students are able to participate in science while learning the science. Providing an authentic learning experience with several components of a course-based research experience (CURE) (Auchincloss et al., 2014), such as data collection and analysis, collaboration, and iteration, can also provide research opportunities to many students who would not normally have access to such opportunities, particularly underserved students and minorities (Estrada et al., 2018).

To this end, we have created a collection of web-based, data-processing applications, called the Astromancer suite. This library includes tools in support of multiple of the modules within Skynet's introductory astronomy curricula, Our Place in Space! (OPIS!) (Reichart, 2021) as well as MWU!, and is where both OPIS! and MWU! students will process their non-image data. Each of these tools has been tailored to its module, combining robust data analysis with pedagogical value. The most recent tool to be added is Gravitymancer, which allows students to upload gravitational-wave event data from the Gravitational Wave Open Science Center (GWOSC) website (Abbott et al., 2023), where raw data from the LIGO-Virgo-KAGRA (LVK) detectors are archived.

Gravitymancer presents students with a real-time look at how the gravitational-wave search is conducted, and a small-scale version of how models are fitted to LVK data. This tool will be an integral part of MWU!'s gravitational-wave module, which is under development now, giving students an up-close experience with one of the newest and most cutting-edge fields in astronomy. This module also dovetails with MWU!'s pulsar module, which precedes it. The Hulse-Taylor pulsar (Hulse and Taylor, 1975), which is an inspiraling pulsar-neutron star system that will one day merge, creating its own gravitational-wave event, serves as a bridge between the two units.

2 The Gravitational-Wave Search

LVK is a collaboration of four massive Michelson interferometers located in three different countries with each respectively 4km, 4km, 3km, and 3km across. The four detectors work simultaneously to detect, record, and triangulate gravitational-wave events caused by merging black holes, and even by merging neutron stars in some cases. The subsequent data processing for an event involves fitting thousands of available models to the observed waveform data, constraining the following parameters: total mass, mass ratio, distance, spins, and signal-to-noise. These models are generated from any number of available waveform 'approximants', all of which have their own special focus on certain aspects of these mergers. The current gravitational-wave search can fit total mass and mass ratio to a fair degree of confidence, with the distance parameter being less certain due to LVK's limited ability to measure orbital inclinations.

3 Gravitymancer

The Gravitymancer tool displays LVK data in two charts simultaneously and is displayed in its entirety in Figure 1 using the dataset from GW150914, which has one of the highest recorded SNR's of all recorded events as of 2023, along with being the very first recorded gravitational wave event (Abbott et al., 2023). The top chart is a spectrogram, which displays the event's spectral power as a function of frequency and time. The bottom chart displays the event's strain, a dimensionless measurement of how much the interferometer was stretched or compressed by gravitational waves, as a function of time. Students then visually match both frequency and strain models to the information in these charts. The frequency model goes first, with students manipulating merger time, total mass, and mass ratio parameters to model the spectrogram. They then fine-tune their solution with the strain model, matching distance/amplitude and phase. We have also included an inclination parameter, which serves more for demonstrating how inclination degenerately affects strain amplitude. In essence, this is how LVK does their gravitational-wave search, except that Gravitymancer uses a grid of models generated from only one approximant, instead of automatically checking thousands of models from multiple approximants.

To make this tool more accessible we have also added a sonification feature that mirrors common sonification implementations with pulsar data. As students match their data, they can generate a sonification file that plays the audio from either the model or the data. This provides an additional dimension to the exploration for sighted and sight-impaired users alike.

3.1 Processing Gravitational Wave Datasets

This tool processes raw gravitational waveform data taken straight from the GWOSC website in the same way that the professional search is done. First, the data are whitened by dividing the frequency-space strain data by the square root of its power spectral density (PSD), flattening the noise in the data across all frequencies. Next, these data are filtered around the frequencies expected for the merger event, where the bandpass is set by the parameters of the model that the data are being compared to. This further suppresses noise from outside of the merger's frequency range. The result is a high signal-to-noise ratio in the processed data, allowing users to clearly see the merger waveform that they are trying to match in the strain chart. This also provides excellent merger parameter fits, as displayed in the accurate distance, total mass, and mass ratio fit in Figure 2. All of this is done server side, and behind the scenes, which made this one of the most challenging Astromancer tools to develop.

3.2 Robust Model Archive

Gravitymancer relies on a library of over 100,000 pre-generated, whitened, and bandpass filtered gravitational-wave models, generated using PyCBC (Nitz et al., 2023). The waveform approximant we chose was IMRPhenomD, a fourth-order approximant calibrated to mass ratios up to 18, and to total masses between 3 and 300, and has been seen to provide sensible results outside of these ranges as well. Our library was generated on a logarithmic grid with 1,000 equal steps in mass ratio between 1 and 10, and 100 equal steps in total mass between 2.5 and 250. As

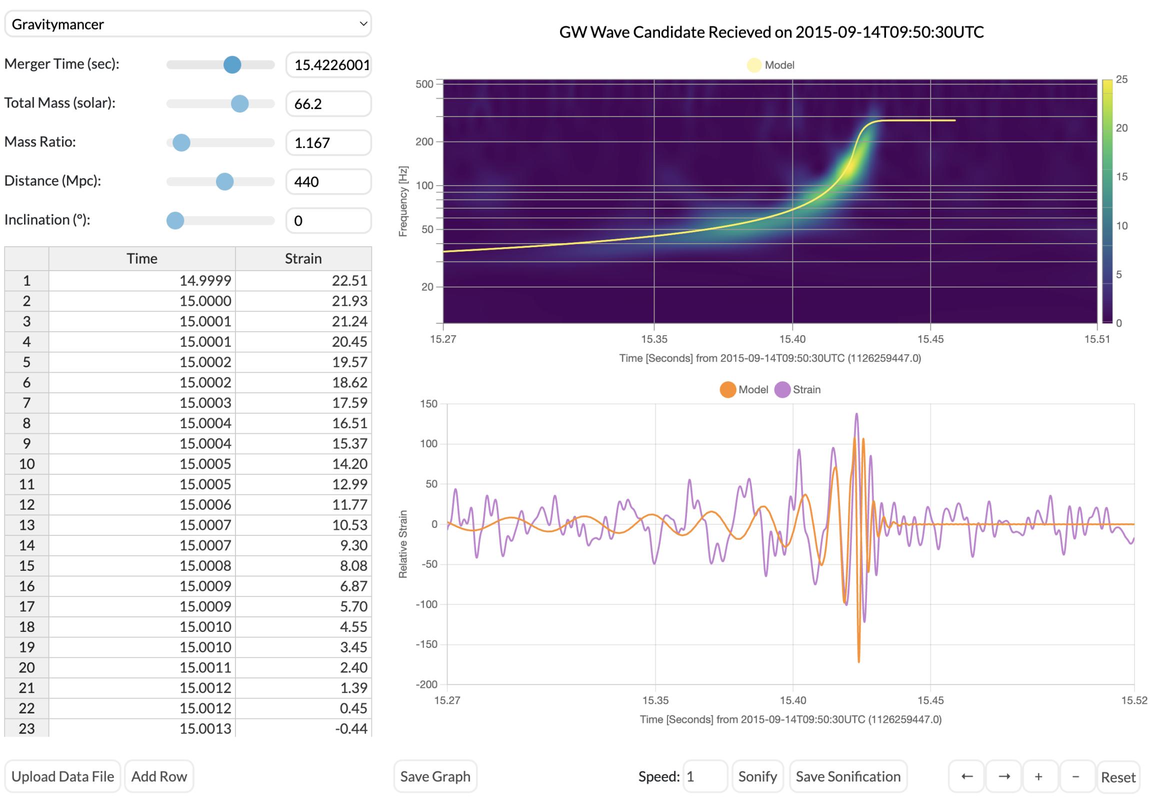

Figure 1. Gravitymancer modeling of GW binary black-hole merger event 150914 in 2015, in this case with total mass, mass ratio, and distance set as provided by GWOSC.

students change either the mass ratio or total mass parameters,

Gravitymancer searches for the model closest to each, and uses

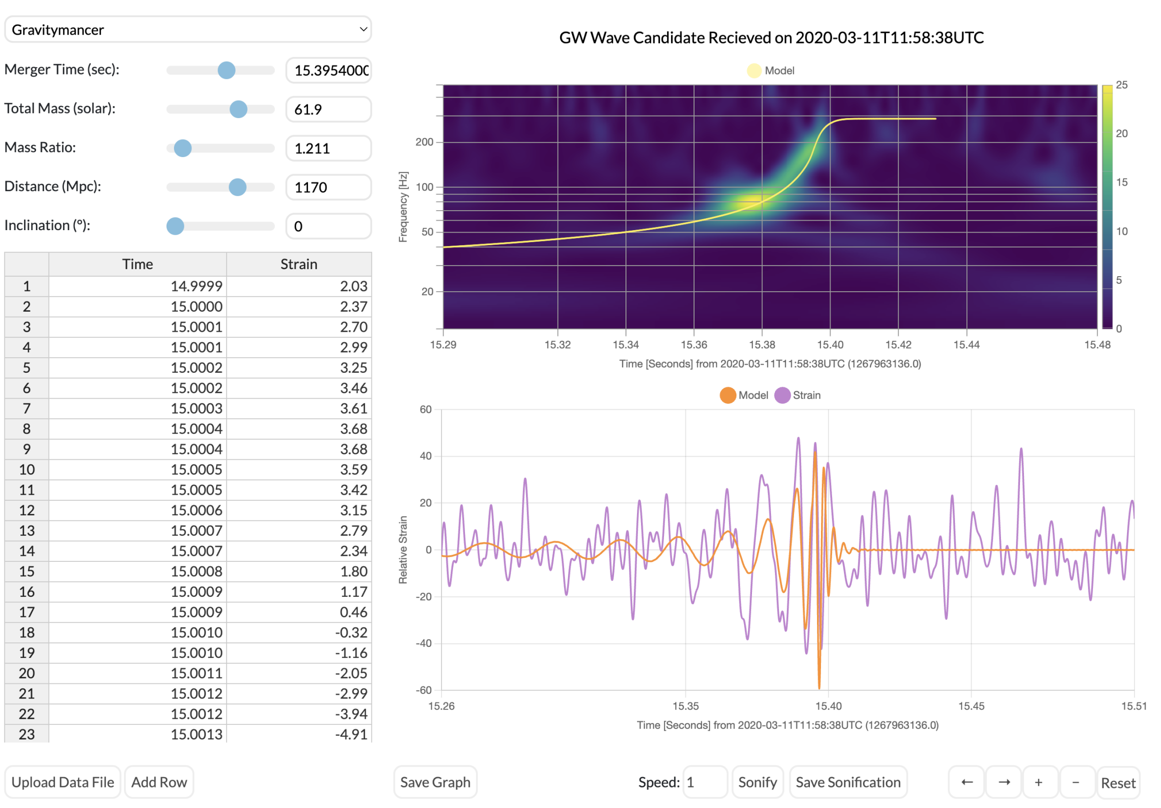

Figure 2. Gravitymancer modeling of GW binary black-hole merger event 200311_115853 in 2020. Note the similar total mass and mass ratio as 150914 in Figure 1, but greater distance/lesser strain amplitude.

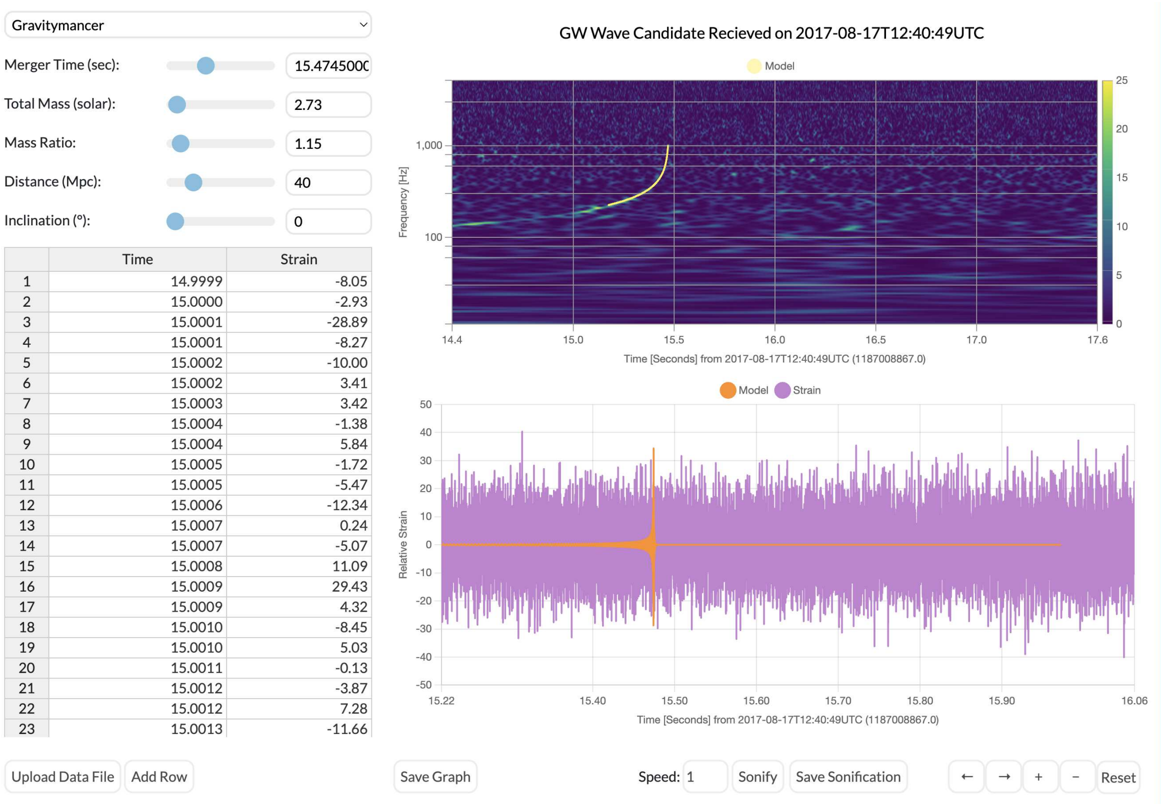

Figure 3. Gravitymancer modeling of GW binary neutron-star merger event 170817 in 2017. Despite being a sub-noise event, students are still able to measure total mass and mass ratio, and set a sensible minimum distance, matching GWOSC.

phase and amplitude scaling relations to interpolate between total-mass grid points. In addition to the processed models, Gravitymancer also stores the bandpass frequencies and raw timeseries waveform counterparts for each grid point. The raw timeseries waveforms are stored for the purpose of signal-to-noise ratio calculations. In testing, the SEOBNRv4 waveform approximant yielded the most accurate SNR calculations, facilitating accurate distance scaling and measurement, as displayed by the proper distance constraint reached in Figure 3 using GW170817, which is the very first recorded gravitational wave event produced by binary neutron stars. Gravitymancer is also designed to be easily updatable, so that its library can evolve alongside new improvements in this young field.

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