Millisecond Pulsar Timing 1: Background and Motivation

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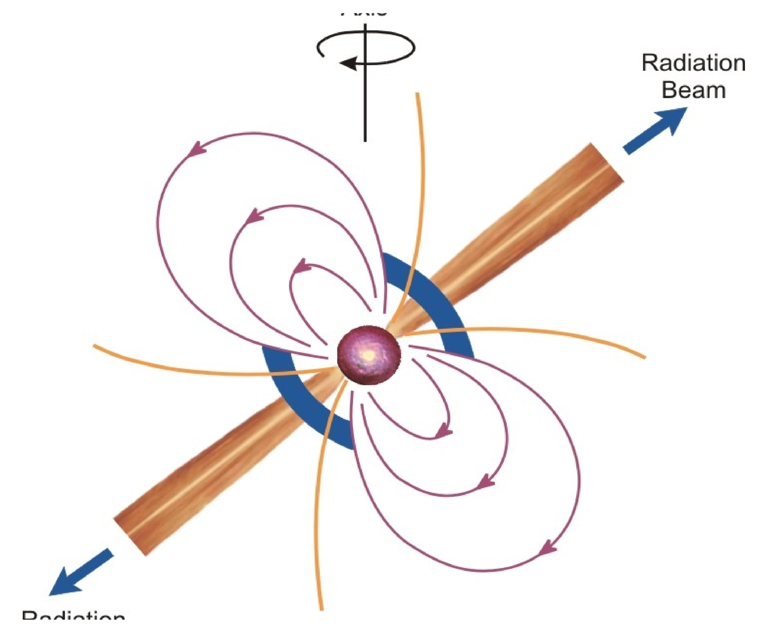
What are Pulsars?

When a giant star explodes in a supernova, one possible type of stellar remnant is called a neutron star. Neutron stars are incredibly dense, having more than 1.1 times the mass of the sun with diameters on the order of 10 km. Due to the conservation of angular momentum, they also rotate very rapidly. Pulsars are highly magnetized neutron stars that emit beams of electromagnetic radiation. As they rotate, their beams sweep through the earth, causing periodic pulses of radio waves that can be detected by radio telescopes.



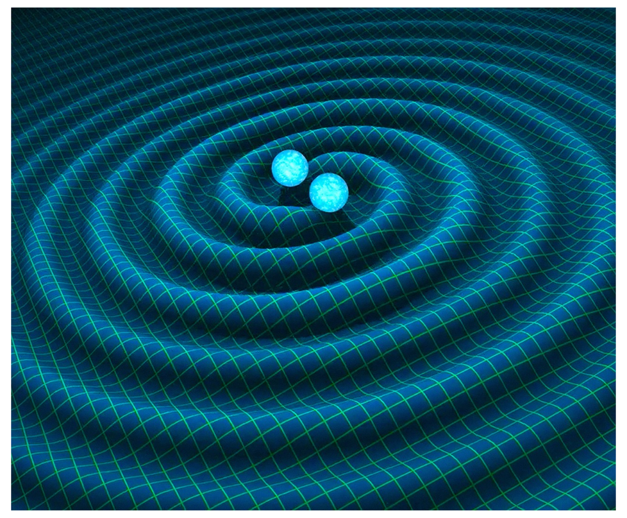
http://www.nrao.edu/

Above: A diagram of a pulsar.

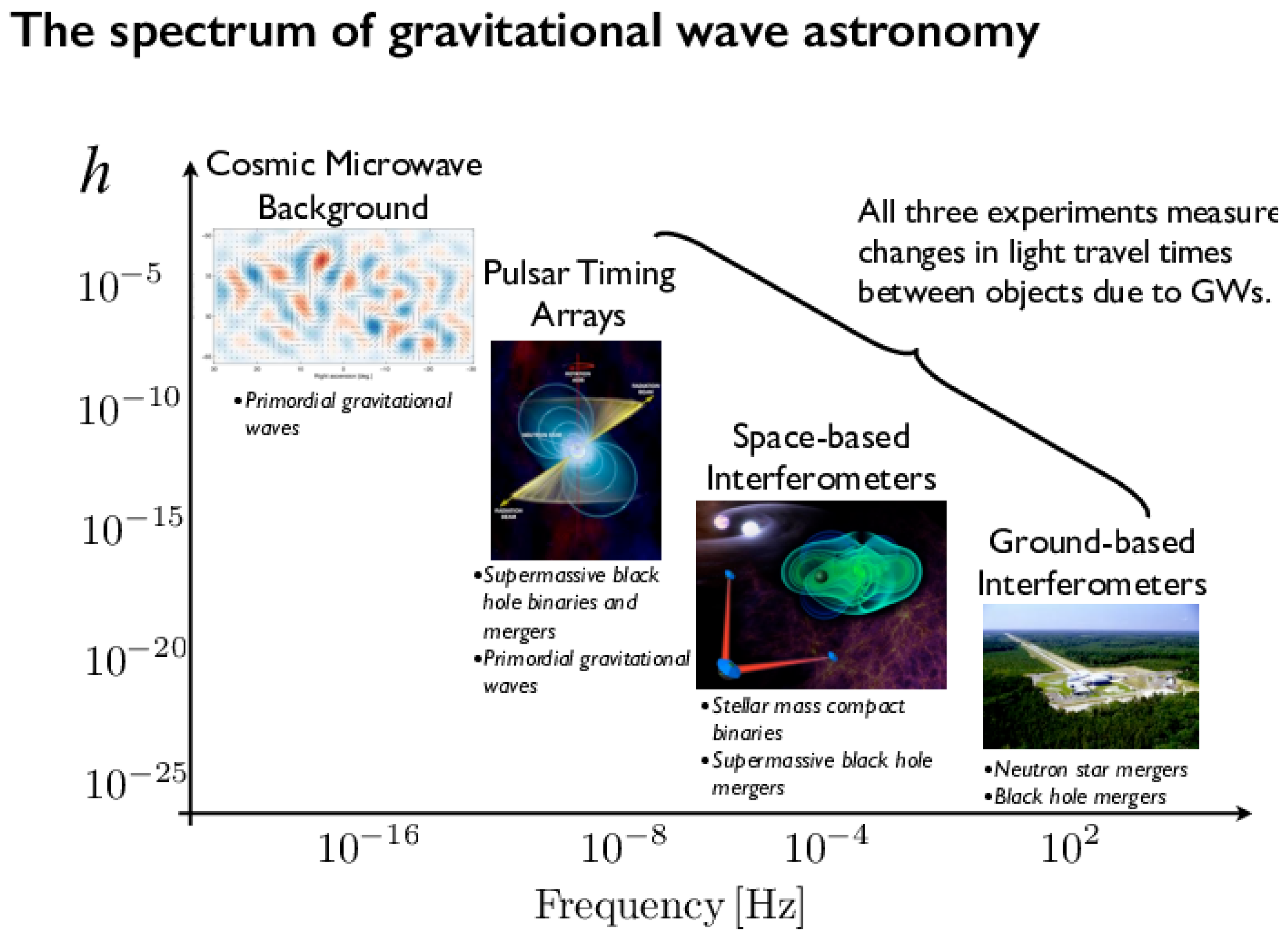
Specifically, our research focused on millisecond pulsars, a subcategory of pulsar with a rotational period of less than 10 milliseconds. Millisecond pulsars are theorized to be older pulsars whose faster rotation comes from their accretion of matter and angular momentum from a binary companion star. Therefore, most of the millisecond pulsars we observe are in binary systems. Because we can detect their pulses extremely precisely, some millisecond pulsars rival atomic clocks as methods of timekeeping.

What are Gravitational Waves?

Our reason for studying pulsars is to try to detect gravitational waves, which are ripples in the "fabric" of spacetime as predicted by Einstein in his theory of general relativity. They are generated by gravitational interactions, such as the merger of black holes, and propagate outward as waves from their sources at the speed of light. Gravitational waves distort spacetime so that the distance along a fixed path may change as it is crossed by a gravitational wave.



Left: An artist's interpretation of colliding black holes creating gravitational waves.
Right: A diagram illustrating the spectrum of gravitational wave astronomy.



http://nanograv.org/ , https://www.nasa.gov/feature/goddard/2016/nsf-s-ligo-has-detected-gravitational-waves

The existence of gravitational waves was confirmed by scientists at LIGO in 2015. LIGO is a ground-based interferometer; it can detect gravitational waves emitted by the mergers of black holes that are on the order of up to 10-50 solar masses.

Pulsar timing arrays are sensitive to gravitational waves of a different sort: those emitted by binaries or mergers of supermassive black holes, with masses of ~10^9 M⊙.

Observations

We made observations with the Arecibo Observatory on-site in Puerto Rico and remotely from Lafayette College. We also used previously collected data, which came from two radio telescopes: Arecibo Observatory in Arecibo, Puerto Rico, and Green Bank Observatory in Green Bank, West Virginia.

Top Right: Arecibo Observatory. With a diameter of 305 meters, it was, until recently, the largest single-dish telescope in the world.

Left: Standing on the platform of the Arecibo telescope.

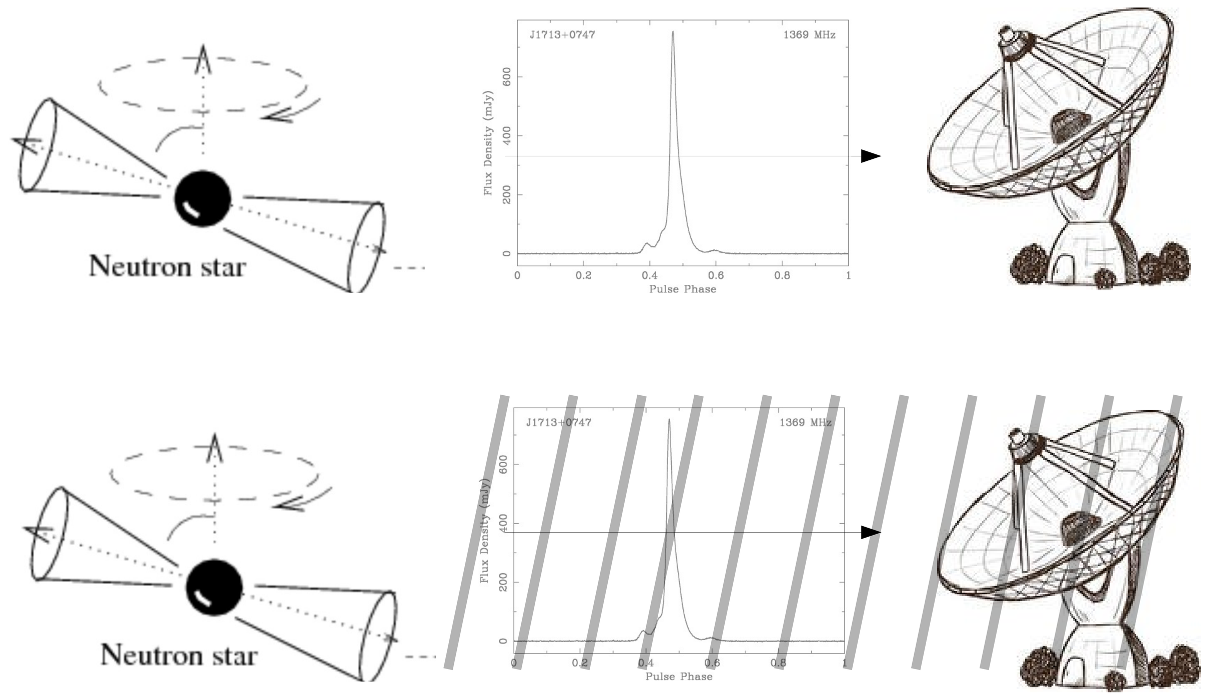
Bottom Center: Green Bank Observatory.

Bottom Right: A view of the platform at Arecibo from below.

http://www.wvcommerce.org, , https://en.wikipedia.org/wiki/Arecibo_Observatory

NANOGrav and Pulsar Timing

As a gravitational wave passes through the Earth, it distorts spacetime and alters the distance between the telescope and its source (the pulsar). Therefore, these pulses take a shorter or longer time to travel to the Earth, affecting the pulse arrival time. Since we can measure the TOA (time of arrival) of millisecond pulsars' pulses with a high degree of precision, we should be able to detect the change caused by the gravitational waves. NANOGrav (North American Nanohertz Observatory for Gravitational Waves) is a group of scientists trying to use pulsar timing arrays to search for gravitational waves in this fashion.



https://inspirehep.net/record/801664/plots, http://www.gograph.com/vector-clip-art/radio-astronomy.html

The top diagram represents a simplified pulsar (distances not to scale) sending pulses to a radio telescope on Earth. The bottom diagram represents that same pulse traveling, now with gravitational waves along its path and causing the path to become longer or shorter.

The Interstellar Medium

One significant complication in pulsar timing is the existence of the interstellar medium (ISM), the matter that lies in the space between star systems (and between us and the pulsar). The ISM is comprised mostly of hydrogen in various states. Pulse propagation is affected by the ionized component of the ISM; therefore, it must be adjusted for. However, the ISM is difficult to model in comparison to other factors affecting pulse arrival time because it is not homogeneous. Due to this, we are not able to predict the magnitude of its effects. Additionally, the ways in which this medium distorts the pulse signal are not all understood.

Our research this summer has been mainly concerned with understanding the effects the ISM has on pulse arrival times and determining appropriate ways to compensate for it. Many of the distortion effects caused by the ISM affect the pulse signal differently at different frequencies. Our research was focused on these frequency-dependent effects. (Note: in this case, we are referring to the frequency of the radio waves that comprise the pulses, rather than the frequency of the pulses themselves).

https://www.space.com/

Acknowledgments

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