
Gravitational Waves: New Observatories for New Astronomy

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This article reviews the current status of gravitational wave astronomy and explains why astronomers are excited about the new generation of gravitational wave detectors. As part of the review we compare and contrast gravitational radiation to the more familiar electromagnetic radiation. We discuss the current indirect experimental evidence for gravitational waves and how current and future gravitational wave detectors will operate as our newest telescopes are pointed at the skies.

Nearly 90 years ago, Albert Einstein made a startling discovery with general relativity—his newly published relativistic description of gravity: Gravity can propagate in waves and carry information from one place in the universe to another, just like photons. It was simple to calculate that these waves would be very weak, and they were generally dismissed as being unobservable and thus unimportant as an experimental probe of general relativity. Other experiments, such as the deflection of starlight, were easily detectable with early 20th-century technology and helped pave the way for the acceptance of general relativity as the correct, modern description of gravity.

Now, almost a century later, technology has caught up with theory, and the detection of gravitational waves is no longer an implausible dream. Large gravitational-wave observatories are being built to listen for faint echoes of gravitational waves that have propagated across the far reaches of the universe to us here on Earth. The detection of gravitational waves from dynamic astrophysical systems will provide astronomers with unprecedented information about the universe,

yielding information that is inaccessible using traditional electromagnetic observations. Gravitational waves will allow the detailed study of dark compact objects, such as black holes, or the interiors of supernova, or possibly the formation of the universe itself.

Multi-spectrum Astronomy

Electromagnetic astronomy makes leaps and bounds in sensitivity and angular resolution by constructing new, more capable observatories on the ground and in space. New technology, such as adaptive optics and interferometry, helps advance our ability to observe the cosmos. However, despite our best efforts, there are regions of the universe that will forever remain shrouded to electromagnetic telescopes because matter impedes the propagation of light to our detectors on or near the Earth.

In some instances, simply changing the wavelength of light allows us to see through intervening matter. This is the case with the Milky Way where vast clouds of dust and gas in the plane of the galaxy block visible light emission from the galactic center, but infrared light is able to get through. There are other cases, however, where photons of any wavelength cannot escape because the matter is too dense. At the core of a supernova, beneath the collapsing envelope of the stellar atmosphere, photons are trapped by the sheer density of matter. Some time after the star explodes, and the expanding shell of gas is thrown off, the remnants of the star expand to a less dense state. At this point the photons find themselves free to travel through space and be received on Earth as messengers from the

explosion. A similar fate befalls photons originating within the first 300,000 years after the big bang. During this era the universe was also very dense, and no form of light could propagate freely. Every photon was perpetually tangled in a sea of dense matter, bouncing around like a fly in a maze of window panes. As the universe expanded it became less dense, and eventually the photons were able to propagate freely. The transition point is known as the “recombination curtain,” and the free streaming photons associated with this era are collectively known as the “cosmic microwave background.”

These kinds of dense environments define the limits of our vision using electromagnetic telescopes. Photons will never arrive from the core of a supernova or from a time before the recombination curtain. It would be great if there was a way to see into these super dense regions, analogous to seeing the center of the galaxy in infrared. Fortunately there is: We can look in gravitational waves.

Unlike electromagnetic radiation, gravitational radiation interacts weakly with matter. Gravitational waves propagate through space freely, taking little notice of the environments they pass through. Gravitational waves are generated by dynamic and energetic motion of matter, as one might find in the core of a collapsing star or in the very early universe. Most importantly, they carry information about times and places in the cosmos that we have no other ways to probe. Detecting gravitational radiation will reveal for the first time the secrets of environments, which have to date been the realm of theoretical calculations and speculation.

In addition to probing environments too dense for light to escape, gravitational waves will provide insight into astronomical systems too compact and dim to resolve with current telescopes. Observations of bumps on neutron stars, stellar mass objects orbiting supermassive black holes, or the final merger of two stellar remnants are all well outside the capabilities of even the most advanced electromagnetic telescopes. By contrast, these systems should be detectable with high confidence in gravitational waves and will provide information that is unobtainable by any other means.

New Eyes on the Universe

Photons love interacting with matter. On the upside, this makes them easy to gather with telescopes

(made of matter) but on the downside, photons are easily distracted by intervening matter during their flight to Earth. In contrast, gravitational waves interact very poorly with matter. As a result, gravitational waves make a great probe of the universe, but they present a significant challenge to designing an astronomical instrument (made of matter) that can sense their passing.

We have strong indirect evidence for the existence of gravitational waves from electromagnetic observations of the Hulse-Taylor binary pulsar and others like it. In the early 1970s, the team of Russell Hulse and Joseph Taylor used radio observations to measure a decrease in the orbital period for the binary pulsar PSR 1913+16. Subsequently they showed that the energy loss associated with the orbital decay rate was consistent with the emission of gravitational waves. For their discovery, Hulse and Taylor won the 1993 Nobel Prize in physics.

Indirect evidence is not the same as having direct observations, and a direct detection of gravitational waves has not yet been made. If we are to detect gravitational waves directly, we need to first understand what must be measured. Gravitational waves are oscillations that stretch and squeeze the fabric of spacetime in a characteristic way that reflects the motion of the emitting system. Similar to electromagnetic radiation, gravitational waves come in two flavors or *polarizations*. These polarization states are referred to as *plus* (+) and *cross* (x) after the pattern of stretching and squeezing they impose on matter that they pass through. The gravitational waves bathing the Earth are expected to be extremely weak. A strong gravitational wave is only expected to stretch (or squeeze) spacetime by the width of an atomic nucleus over a distance of 5 million kilometers! Detecting its presence will be like looking for an atom-size change in distance between the ends of a ruler 13 times as long as the distance between the Earth and the Moon!

Direct detection of something as weak as a gravitational wave requires a not-so-conventional observatory.¹ Gravitational wave detectors fall into two broad categories: resonant bar and interferometric detectors. Bar detectors listen for gravitational waves by monitoring acoustic modes in an isolated metallic bar. When a gravitational wave with a frequency similar to the resonant frequency of the bar stretches and

Table I. A representative list of gravitational wave detectors either operational now or in their developmental phase.

Detector	Type	Location	Operational
EXPLORER	Resonant Bar	Geneva, Switz.	1984
ALLEGRO	Resonant Bar	Baton Rouge, LA, USA	1986
NAUTILUS	Resonant Bar	Rome, Italy	1994
AURIGA	Resonant Bar	Lengaro, Italy	1997
TAMA	Interferometer	Mitaka, Japan	1999
LIGO	Interferometer	Livingston, LA, USA, Hanford, WA, USA	2002
GEO 600	Interferometer	Hannover, Ger.	2002
VIRGO	Interferometer	Cascina, Italy	2006
LISA	Interferometer	Space	~2014

squeezes the bar, it will “ring.” Joseph Weber (1919-2000) brought the first bar detector online in the 1960s and today there are several operating around the world. In Table I we present a representative list of detectors currently in use.

Interferometric detectors operate on the principle that a gravitational wave stretches and squeezes spacetime, changing the proper distance between two fixed masses when it passes by. A passing gravitational wave is detected by noting a change in the interference pattern created when laser light from two different arms of the interferometer is recombined. The interference pattern change occurs when the light travel time of the laser in one arm changes relative to the other. In the United States, the Laser Interferometer Gravitational-wave Observatory (LIGO) operates two sites: a 4-km arm interferometer in Livingston, LA, and two interferometers (4 km and 2 km) in Hanford, WA. Several interferometric gravitational wave detectors are now in operation (see Table I) and currently are approaching sensitivities that should make a direct detection in the near future.

Work is also progressing on a space-based mission to detect gravitational waves in a lower frequency range than ground-based detectors. The Laser Interferometer Space Antenna (LISA) is a joint NASA-ESA mission currently scheduled to launch around 2014. LISA will operate as an interferometric gravitational wave detector but with arms that are 5 million kilometers long!

Different gravitational wave detectors will detect sources in different gravitational wave frequency bands. LIGO is sensitive to high-frequency gravitational waves (around 1000 Hz, with wavelengths of 300 km), while LISA will be sensitive to lower frequency gravitational radiation (around 1 mHz or wavelengths of 300 million km). In this way, gravitational wave detectors will probe different aspects of the universe, much like traditional telescopes do when observing, for example, in infrared or radio.

Gravitational Wave Astronomy

Gravitational wave astronomy is a new and vibrant field of observational astronomy, just entering an era where detectors capable of detecting signals from space are becoming operational. At the end of 2005, the LIGO detectors began their first year-long science run at their target design sensitivity, giving us our first deep probe of the cosmos in gravitational waves. Our expectation is that the deep reaches of space are alive with gravitational wave signals from black holes, neutron stars, supernovae, and other highly energetic events, and within the next decade we will be detecting them on a regular basis.

The current generation of gravitational wave observatories is only our first step toward looking at the universe with new eyes and ears, in much the same spirit as Grote Reber’s first radio antenna or Isaac Newton’s first reflecting telescope. As with all branches of astronomy, new windows on the universe resolve old debates about the nature of distant astrophysical systems and pose new mysteries and questions about the cosmos. Gravitational wave astronomy is expected to be no different.

Acknowledgments

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Select Introductory Gravitational Wave Resources

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The authors are all members of the Center for Gravitational Wave Physics, an NSF Physics Frontier Center at The Pennsylvania State University. They work in the emerging field of gravitational wave phenomenology, which sits at the interface between modern gravitational theory, astrophysics, and engineering. Their expertise spans all these fields with the common goal of understanding how gravitational wave observations can reveal the story gravity has to tell about high energy astrophysical phenomena.

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