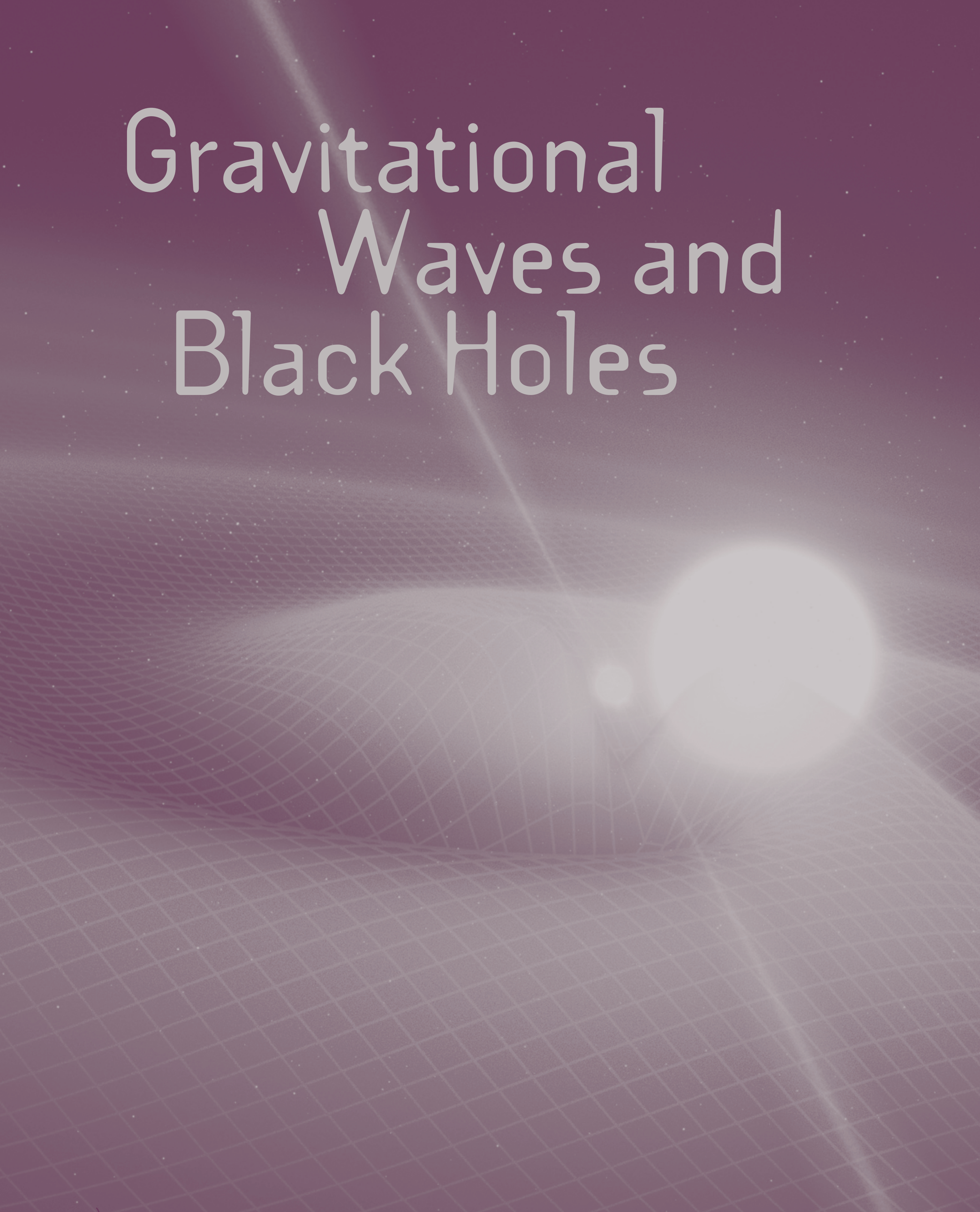
Gravitational Waves and Black Holes



The Enigmatic Children of General Relativity

by Matthew Evans

You may have heard that GRAVITATIONAL WAVES were recently detected. If you are old enough, you may recall that this was not the first time you heard such a claim. And you are likely young enough that it won't be the last.

SINCE THEIR CONCEPTION A CENTURY AGO BY EINSTEIN, gravitational waves have proven an elusive child of his far-reaching theory of general relativity. The mysterious nature of gravitational waves comes largely from the fact that, unlike other waves, they do not propagate in some material medium, but rather move as distortions of space and time.

General relativity produced a number of other fanciful sounding offspring, like the mind-bending denizens of our Universe known as BLACK HOLES. Originally considered by many as a mathematical curiosity, or even evidence for a flaw in the theory, black holes have come to be accepted as central players in galaxy formation

FIGURE 1

Artist's rendition of a quasar gathering fuel in the early Universe. *The supermassive black hole at its core produces a strong beam of radiation that can be seen across the Universe. [Credit: ESO/M. Kornmesser]*

and the central engine behind the great dynamos known as QUASARS, which are bright enough to be seen across the universe (*Fig. 1*).

Unlike black holes, gravitational waves continue to elude detection, though not for a lack of trying on the part of physicists. So, why do gravitational waves pass through us undetected, and why should we be bothered by their escape?

Essentially everything we know about the Universe we learn from the light that comes to us from far-away objects, such as stars, galaxies and galaxy clusters. While over the last century we have opened our eyes to a wide range of electromagnetic radiation from radio waves to gamma rays, we are still fundamentally *deaf* to the Universe.

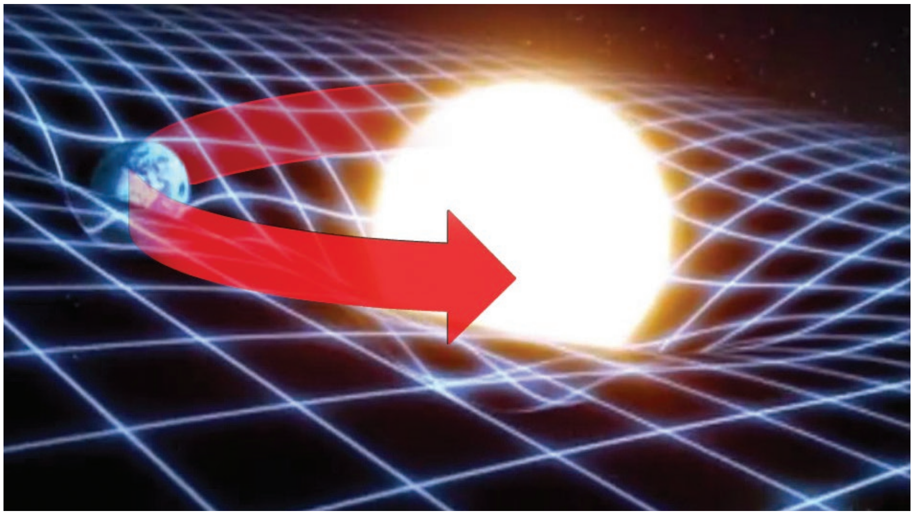


FIGURE 2

Space-time distorted by the Sun is responsible for the Earth's orbit. *(Credit: WGBH-TV Boston)*

Imagine for a moment an explosion or a lightning strike. We observe each of these in two ways: the flash of light that comes from the heat produced as energy is released, and later, the sound that propagates to us through the air. The first of these, a thermal process, is driven by the fast and incoherent motion of the atoms and molecules, which are heated in the explosion. The second, sound, is the slow and coherent motion of atoms in the air. These two channels carry different information and move differently through space.

You can probably imagine the sound of an explosion, but can you imagine the sound of a supernova? Probably not very well, for while many supernovae have been seen, no human has ever heard one.

Gravitational waves are like sounds that propagate across the vast empty spaces between stars and galaxies, and the instruments currently working to detect them will allow us to *hear* the things that go bump in the Universe.

What sounds will we hear with gravitational waves?

Imagine hitting a long steel rail, of the sort used in railroads, with a sledgehammer while a friend far away listens with her ear pressed to the rail. The sound of the impact would travel quickly to her ear, thanks to the stiffness of the rail. But for the same reason, a light touch will not suffice to make an audible transmission. You need something hard and preferably massive to make your signal heard.

Gravity operates, according to Einstein, by allowing massive objects to bend the space around them—often depicted in two dimensions with a ball placed on a rubber sheet (*Fig. 2*). Just as you needed a sledgehammer to bend the steel rail and cause a wave to propagate outward, so you need something massive and fast-moving to bend space and cause it to vibrate. Space, or in the more precise language of relativity, SPACE-TIME, is roughly 22 orders of magnitude stiffer than steel, so a very large sledgehammer is required to send even a weak signal.

The only objects in the Universe massive and dense enough to produce gravitational waves at audible frequencies are black holes and their little brothers known as NEUTRON STARS. Black holes and neutron stars, which are the remnants of massive stars that burned all their fuel and collapsed, are unimaginably dense and compact objects; other stars seem like cotton candy by comparison. Like their

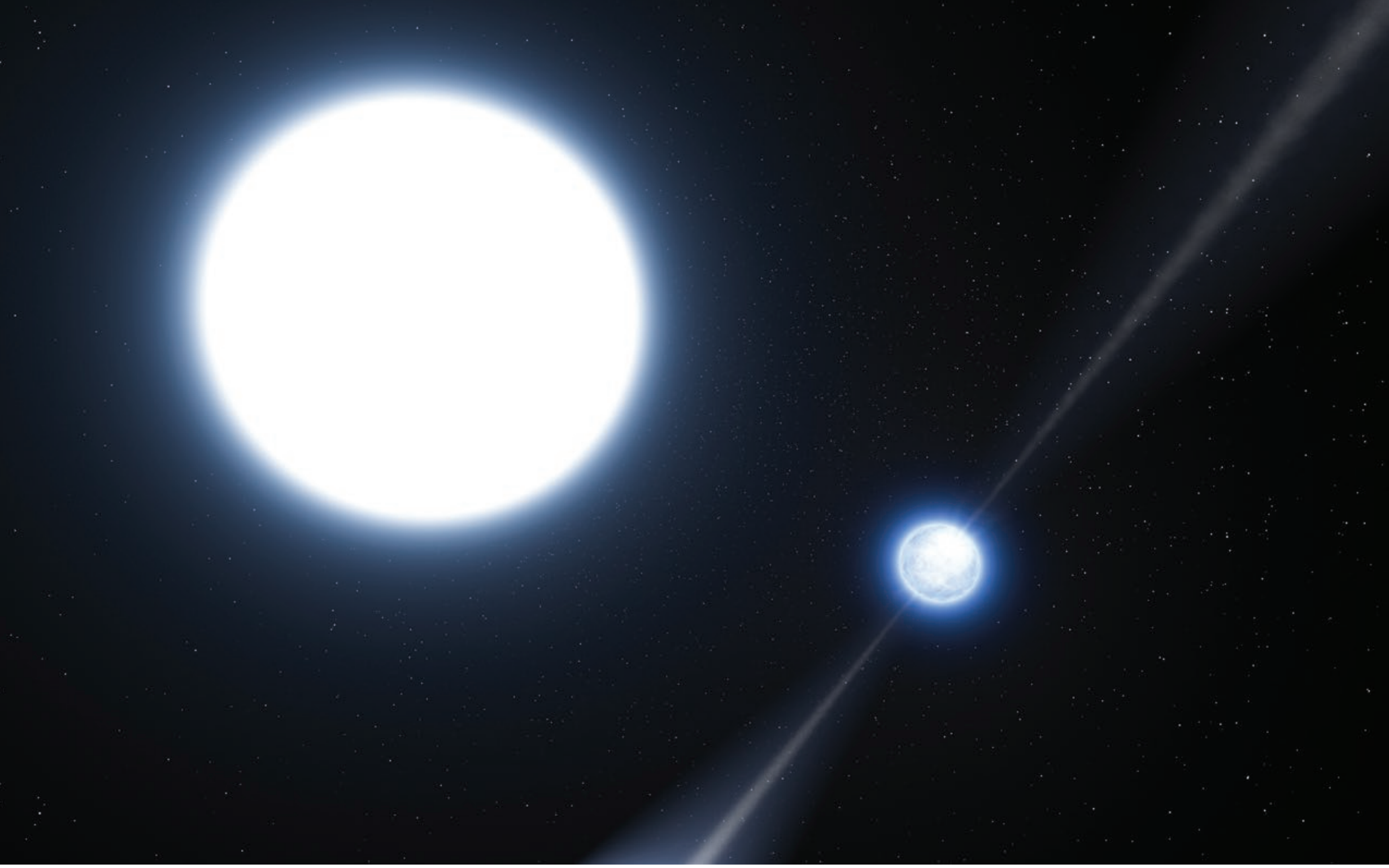


FIGURE 3A

Illustration of a binary system containing a dwarf star and a compact object. *[Credit: ESO/L. Calçada]*

progenitors, these compact objects can come in pairs that orbit each other, and in so doing rhythmically bend the space-time around them to produce propagating waves (*Figs. 3a and 3b*).

In Newton's theory of gravity, the motions of planets and stars are eternal and unchanging, but in general relativity gravitational waves carry energy away from orbiting stars, causing their orbit to slowly shrink until finally the stars are so close together that they merge. Orbiting pairs of black holes and neutron stars, known collectively as COMPACT BINARIES, can move at speeds approaching the speed of light, and go around each other hundreds of times per second before the binary coalesces into a single black hole. If we could hear such a thing, it would sound like a drawn-out "Whooop!" moving up in frequency and getting louder until it pops at the end.

While compact binaries are likely the loudest thing in the Universe, there are a number of other promising sources of gravitational waves. For instance, neutron stars, yet to transition to a featureless black hole, can have small mountains on them. A mountain on a rapidly rotating neutron star can produce a pure tone audible at great distances. A prime candidate for this is the neutron star born in a supernova that occurred in 1054 and produced the Crab Nebula, which we should hear as a tone just below 60Hz, or A#1 on the music scale.

Supernovae themselves are also a likely source of audible gravitational waves, though these violent events are likely to sound a lot like they look: "BOOM!"

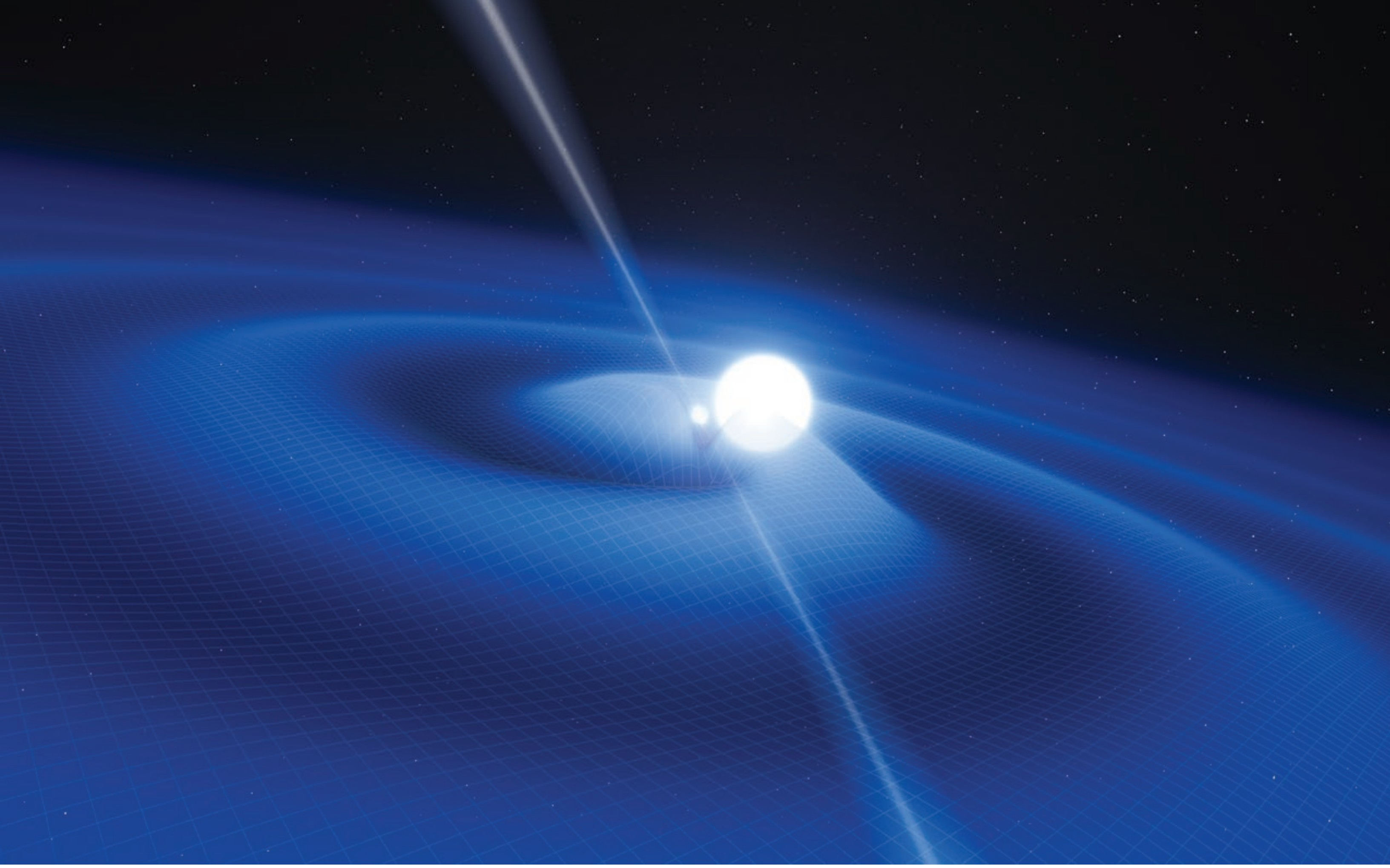


FIGURE 3B

The distortions of space-time are overlaid on the illustration. *The first clear observations of orbiting binary stars losing energy to gravitational waves were made by Hulse and Taylor in the late 1970s (for which they later won the Nobel prize). Several more recent observations, like those of the system PSR J0348+0432 shown here, have confirmed these early observations. [Credit: ESO/L. Calçada]*

The challenge of gravitational wave detection

You might imagine that a passing gravitational wave would bend the space around us enough to cause audible sound waves in the atmosphere; after all, our ears are very sensitive and can detect a change in air pressure of less than one part in a billion. Unfortunately, despite their incredible mass and speed, even a pair of orbiting black holes is unable to make truly audible gravitational waves. Calculations show that we need an instrument at least a trillion times (or, 12 orders of magnitude) more sensitive than our ears to hear gravitational waves. Physics doesn't allow for a stronger source, so we will need to build a very sensitive ear.

Initial attempts to detect gravitational waves as they pass through the Earth were made in the 1960s by Joseph Weber. He built large aluminum bars in the hope that a passing wave would make the bars ring like giant bells, and in 1969 he published results claiming just such an event. Other bar detectors were subsequently built around the world, but Weber's results were not reproducible and it eventually became clear that he had not, in fact, detected gravitational waves. While Weber's work did not bear fruit, a seed had been planted: detection of gravitational waves was clearly difficult, but not inconceivable.

Shortly after Weber published his flawed results, strong support for the existence of gravitational waves came from observations of a pair of neutron stars located 21,000 light years from Earth. One of the neutron stars in the pair was detected,

FIGURE 4

***Research to build and improve LIGO has been ongoing at MIT since 1971**, initially led by Prof. Rainer Weiss and now by Profs. Nergis Mavalvala and Matthew Evans. (Credit: LIGO Laboratory/P. Kwee)*

thanks to its spin and magnetic field, as a pulsating source of radio emission. The clock-like regularity of the radio pulses allowed researchers Russell Hulse and Joseph Taylor to track the motion of the neutron stars, and to show that they were losing orbital energy to gravitational waves exactly as expected according to Einstein's theory of general relativity (*Fig. 3b, page 43*).

In the 1980s, researchers led by Prof. Rainer Weiss at MIT devised a new kind of gravitational wave detector that promised better sensitivity than the Weber bar, by more than a factor of a million. Instead of using great metal cylinders, these INTERFEROMETRIC DETECTORS use ultra-stable laser beams projected over long distances that can detect a pair of neutron stars in the last few minutes before their orbit collapses (*Fig. 4*). The range of detection is up to a distance of 50 million light years—far enough to include not just our entire galaxy, but hundreds of neighboring galaxies.

In the early 1990s, the Laser Interferometer Gravitational-Wave Observatory (LIGO) project was created to build and operate two such interferometric detectors in the United States, while similar detectors were being built in Italy, Germany and Japan. This international network of detectors gathered several years of data in the mid-2000s, although no gravitational waves were detected. While disappointing, this was not a great surprise to the researchers who had built them.

The first generation of interferometric detectors was a huge leap forward in measurement technology and achieved unprecedented precision, but a second generation would be required to capitalize on all that had been learned and to make gravitational wave detection a reality.

FIGURE 5

***A laser interferometer for gravitational wave detection**, located in Livingston, LA. This is one of two such facilities in the U.S. that form the backbone of a global network of gravitational wave detectors. (Credit: LIGO Laboratory)*

The second generation of interferometric detectors in the United States, known as ADVANCED LIGO, finished construction in early 2015 (*Fig. 5*). MIT and Caltech researchers at both LIGO observatories are working to bring these detectors to their design sensitivity, and have already achieved a factor-of-three improvement over the first generation LIGO detectors. Before the end of 2015, work on the detectors will be halted for a few months to listen for gravitational waves, although the odds of detection before the end of this year are still not promising.[1]

Starting in mid-2016, the Advanced LIGO detectors will begin collecting high sensitivity data with increasing frequency, and other detectors around the world are expected to join the search in 2017. With these multi-kilometer interferometric "hearing aids" operating around the globe, gravitational waves carrying the sounds of the Universe will become audible.

In 1916 Einstein wrote, "In any case one can think of, [the gravitational wave amplitude] will have a practically vanishing value." Soon, 100 years will have passed since he predicted the existence of these minute distortions of space-time and the likely impossibility of their detection. Yet technology, research and pure audacity have accomplished that which even Einstein could not foresee, and at last we will cease to be deaf.

For further information about LIGO, visit *www.ligo.org/multimedia.php*.

REFERENCE

[1] In May of 2014, the BICEP2 collaboration announced the detection of gravitational waves imprinted on the Cosmic Microwave Background (CMB). The reported gravitational waves originated not with black holes or neutron stars, but rather as quantum fluctuations of the Big Bang itself. Unfortunately, the validity of this second "direct detection of gravitational waves" was quickly called into question, and subsequently discredited. For more information, visit *bicepkeck.org*.

MATTHEW EVANS' *research is focused on gravitational wave detector instrument science. The U.S. effort to detect gravitational waves is currently upgrading the Initial Laser Interferometer Gravitational-Wave Observatory (LIGO) detectors to Advanced LIGO, with an order of magnitude improvement in astrophysical reach. The Advanced LIGO detectors began taking data in 2015, and should approach design sensitivity over the next five years. Direct detection of gravitational waves is expected to occur during that period.*

In addition to Evans' work on the Advanced LIGO detectors in Hanford, WA, and Livingston, LA, in his MIT lab Evans explores the physical processes that set fundamental limits on the sensitivity of future gravitational wave detectors. Of particular interest are the quantum and thermal limitations that have the strongest impact on ground-based detectors like LIGO, which also play a role in the related fields of ultra-stable frequency references and macroscopic quantum measurement (MQM).

Matthew Evans received his B.S. in physics from Harvey Mudd College in 1996 and his PhD from the California Institute of Technology in 2002. He continued his work on LIGO as a postdoctoral scholar at Caltech, before moving to the European Gravitational Observatory to work on the Virgo project. In 2006 Evans took a position at MIT as a research scientist working on the Advanced LIGO project, and moved to his current position as an assistant professor of physics at MIT in January 2013. His graduate and postdoctoral work have involved many aspects of ground-based gravitational wave instrument science, with special focus on modeling and control of kilometer-scale resonant interferometers.

For a list of Prof. Evans' selected publications, please visit web.mit.edu/physics/people/faculty/evans_matthew.html.