The detection of the Universe's background gravitational wave radiation: a scientific triumph

Don Barrett
3 July 2023

"Count what is countable, measure what is measurable, and what is not measurable, make measurable"—attributed to Galileo Galilei

The detection of a predicted universal background of gravitational waves rippling across the fabric of space-time was announced last Wednesday by the NANOGrav consortium of over 190 scientists at more than 70 institutions. Like the very first detection of gravitational waves themselves, made just eight years ago, it represents a triumph of mankind's increasing technical mastery of the natural world.

The 2015 experimental discovery of gravitational waves targeted "high frequency" waves produced by merging compact objects weighing around the mass of heavy stars, whose oscillations have periods in the range from a fraction of a second to several seconds. This week's announcement, using an entirely different technique, probes a very different frequency range of waves whose periods range from months to decades. In doing so, it probes a very different set of physical phenomena but confirms the same underlying physical principle, that matter in motion also sets space-time into rippling motion.

The NANOGrav discovery builds upon decades of work in opening gravitational radiation as a new window into probing the universe and some of its most exotic elements and builds atop a great edifice of physics whose foundation was laid in the opening years of the 20th century by Albert Einstein in his theories of Special and General Relativity. That such a large consortium and such an immense undertaking could be confidently assembled and brought to fruition is itself a validation of the materialist conception of nature and the harmonious and comprehensive achievements in physics over the past two centuries.

To properly explain this week's announcement requires a digression into the history of gravitational waves and their background. Einstein carried to its natural conclusion the idea of Nicolaus Copernicus (1473-1543) that the Earth was not the center of the Universe: he modified and extended the tremendously successful physical theories of Isaac Newton (1642-1727) so that they had no presumption of *any* special "center" or reference frame from which physical laws emerged. To make the unification, he had to integrate time itself in a fundamentally new way into the mathematical fabric on which physical laws of motion were built. With his General Relativity of 1915, he additionally incorporated curvature into this fabric to describe the motion of bodies acting under the influence of gravity.

A common summary of General Relativity is that matter tells space how to bend and bent space tells matter how to move. But behind this simple explanation lies fiendishly difficult mathematics and predictions once thought so exotic that some felt they would forever remain an exercise in pure thought.

General Relativity and astronomy

The impact of Einstein's theory and the equally transformative introduction of the new Quantum Mechanics into physical law wrought a qualitative reformation in astronomy. Oddities were already piling up: a new class of object, the "white dwarf," had by 1914 already stretched physical conceptions based on prior knowledge to their limits. The physicist Arthur Eddington would write in his *Stars and Atoms* of 1927:

> We learn about the stars by receiving and interpreting the messages which their light brings to us. The message of the companion of Sirius when it was decoded ran: "I am composed of material 3,000 times denser than anything you have ever come across; a ton of my material would be a little nugget that you could put in a matchbox." What reply can one make to such a message? The reply which most of us made in 1914 was—"Shut up. Don't talk nonsense."

And yet only three years later in 1930 the physical nature, drawing from both Relativity and Quantum Mechanics, of such "white dwarf" stars would be worked out by Subrahmanyan Chandrasekhar, and a limit to their mass derived. And four years following that, even more exotic objects would be hypothesized.

The discovery of the atomic nucleus in 1906 by Ernest Rutherford had revealed the astonishing truth that most of the mass of an atom was localized in its very compact nucleus: and that most of the atom itself was empty space. Rutherford aimed high-speed helium atoms (called alpha particles) at a very thin foil of gold. Most passed through unaffected or with only the slightest deviation. But for a few, Rutherford would later recount, "It was quite the most incredible event that has ever happened to me in my life. It was almost as incredible as if you fired a 15-inch shell at a piece of tissue paper and it came back and hit you." Those alpha particles had made rare hits on the tiny gold nucleus and bounced back, revealing the concentration of mass inside the atom. That most passed through undeflected revealed that most of the space inside the atom was empty.

And so, in 1934, Fritz Zwicky would hypothesize an even more exotic object, the "neutron star" (just two years after the discovery of the particle whose name it bore), in which the empty space of atoms was eliminated, and the entire star was at the density of the matter of the atomic nucleus. In it, the density was not a mere 3,000 times higher than anything ordinary, but yet another millionfold higher, such that a tablespoon's volume would have similar mass to Mount Everest. By the end of the decade, physicists had made the first calculations of the structures and limits on such stars. Zwicky correctly surmised that the violence of rare supernovae explosions would necessarily involve energies and densities out of which such exotic objects could emerge, though none immediately saw any prospects for their detection.

But astronomy marched forward. The century saw the expansion of the range of telescopes from visible light to the longer wavelengths of radio (and eventually to all wavelengths of the electromagnetic spectrum), and one fruit of this labor was the detection of peculiar radio sources that chirped with astonishing precision and that would come to be known as "pulsars."

The first, detected by Jocelyn Bell in 1968, was so novel in this periodicity that Bell scribbled next to the peaks on the strip chart showing radio emission the letters "LGM?"—wondering whether alien intelligence or "little green men" were its authors. Once searches were targeted for such objects, many more followed; over 3,000 are now known. And with them, physicist Thomas Gold would make a compelling case that these were in fact Zwicky's neutron stars, but with a twist: the magnetic fields which had once threaded their parent star had been compressed by the same factor as the neutron star itself, intensifying them billionfold or more (in some cases more than a quadrillion) over the magnetic field that orients compasses on the Earth. These magnetic fields, locked into the rapidly spun up neutron stars (whose spin also increases during their compression), would generally lie at some offset from the rotation axis, creating the effect of a lighthouse whose rotating beam periodically announced itself as the neutron star.

And finally, only months after Einstein's publication of his theory of General Relativity, the physicist Karl Schwarzschild, working on the German front with Russia in World War I in 1916, would produce the first exact mathematical solution to Einstein's equations of General Relativity, and die only months later at age 42 from illness exacerbated by his time in the trenches. Schwarzschild's work predicted the existence of an even more exotic object, one in which the density of matter had grown beyond the ability of space-time to support it, with it folding up into a "black hole" in space-time itself, possessing mass and a type of one-way horizon, but little else. And yet motivated by Bell's 1968 discovery and Gold's identification of it as a neutron star, by 1971 several astronomers would independently make the case that another source, Cygnus X-1, identified by new space-borne x-ray telescopes, was the first identified astrophysical black hole.

Gravitational waves

That the mathematical framework of General Relativity admitted "wave-like" solutions rippling across their description of space-time was evident from the start. Einstein predicted their existence only months after he developed his theory's framework but considered them of "negligible practical effect." But even their author changed his mind—several times!—as to whether these represented a real physical phenomenon or arose as an artifact of the mathematics, in which both matter and wave moved in lockstep and produced no tangible external action. It was 48 years later and nine years after Einstein's death, in 1964, that the physicist Richard Feynman gave a compelling argument that the waves would actually result in the observable motion of matter, elevating them from a curiosity into something potentially measurable.

Within the decade, the first efforts to actually detect such waves permeating the Universe were made by Joseph Weber at the University of Maryland, and eventually by many small groups. But even as efforts progressed to blindly detect gravitational waves, astrophysics moved forward to better understand the population of phenomena in the universe that would create these waves, and to estimate their intensity. And it turned out that the extreme weakness of the waves, predicted by General Relativity, also made them excellent probes of the most extreme objects, whose understanding itself required the mastery of Relativity, neutron stars and black holes, in their interactions with other objects.

The results were initially demoralizing. The strongest likely waves that were forecast to routinely occur, lasting only seconds, would be expected to move matter by an almost inconceivably small amount: by a thousandth the width of an individual proton over a path length of a few kilometers. The precision inherent in such a measure is equivalent to measuring the distance to the nearest star to a fineness smaller than the width of a human hair.

But astrophysical sources would reveal their existence in another way: most stars are part of multiple systems, and the same processes that give rise to neutron stars or black holes at the end of their lifetime can occur to their companions as well, producing binary or higher systems of these compact objects. If the objects are in very tight, fast orbits, their gravitational wave emission is so energetic that it materially changes their orbits as energy is lost from the system to this radiation.

In 1974, Russell Hulse, working with Joseph Taylor Jr., discovered the first known "binary" neutron star, in which a radio-"loud" pulsar is seen to change its cadence slightly but repeatably every 7.75 hours, evidence of it orbiting very close by another compact but invisible object, now ascribed to be a second neutron star whose radio pulsations are either too faint or mis-aimed to be detectable. Analysis of the system showed that both neutron stars weigh about half again more than our Sun, yet the two, each the size of a small city, orbit one another in a volume that would itself fit inside our Sun.

The observational precision possible for some measurements when you have a high-precision clock orbiting another object is astonishing. Within a short period of time, it was seen that the orbit was varying in precisely the way expected by General Relativity, another triumph for its predictive power, and that the system was shrinking from the loss of energy through gravitational wave radiation by about 3.5 meters a year (in an orbit with a close approach of about half a million miles), predicting a final inspiral and merger in about 300 million years.

Experimental discovery of gravitational waves

As the WSWS has described previously, the development of technology to confirm these predictions moved from the efforts of individual and poorly funded researchers to a coordinated international effort in the 1980s and 1990s, with the Laser Interferometer Gravitational-wave Observatory (LIGO) entering operation at an initial low sensitivity in 2002. The lack of detections in its first 13 years of operation was disappointing but not surprising: the community was well aware that its initial sensitivity would only record exceptional events.

But from the start, the project planned upgrades made possible by anticipated and commissioned technology development. An "advanced" version began operation in September 2015 with about 60 times the expected detection rate of the initial project and made its first detection during engineering commissioning even before routine scientific observations began. Since then, nearly a hundred detections have been made, with a new and even more sensitive version of the LIGO detectors entering service on May 24 of this year. What was once thought far beyond human capability is now, thanks to achievements across the sciences and the organized labor of thousands, a routine measurement.

NANOGrav—the North American Nanohertz Observatory for Gravitational Waves

The same science-based confidence and optimism that enabled decades of work on LIGO, leading to the realization of its aspirations, were at work in the building of the NANOGrav collaboration, which was assembled in 2007, eight years before LIGO would finally achieve its first success, and funded in 2010, five years before LIGO finally triumphed.

LIGO was built to probe a particular wavelength of gravitational wave, those produced through mergers of objects massing a few times to a few tens of times that of the Sun. But other astrophysical processes produce gravitational waves, and the existence of detected black holes, with masses millions to billions of times the mass of our Sun, in the centers of some galaxies shows that much larger mergers must take place in the Universe. Some large galactic mergers result in binary supermassive black holes at the centers of their galaxies, which take years to orbit one another.

Such mergers and binary black holes, despite pouring out far more energy, would be difficult or impossible to detect with LIGO because they operate on much larger timescales and produce waves of much larger wavelengths.

While much rarer, such mergers, plus the drumbeat of orbiting supermassive binary black holes, would create an overall “sloshing” of space-time just as distant storms on an ocean leave their imprint on waves crashing onto a shore. And it is possible that the detection and ultimate characterization of such long-wavelength gravitational radiation in detail may reveal yet-unknown astrophysical processes at work, or a signature of the early Universe.

NANOGrav’s technology aims at detection of gravitational waves whose timescale is not seconds but rather years or decades. Since the physical size of such a detector along the lines of LIGO would have to be of interstellar scale, other techniques must be used rather than construction. An idea put forward in the 1970s by Soviet astronomer Mikhail Sazhin and American astronomer Steven Detweiler cleverly uses objects understood by General Relativity, pulsars, as a probe of another prediction of General Relativity, gravitational radiation.

This technique, adopted by NANOGrav, uses the sightlines to dozens (now 68 and growing) of the most rapidly spinning and stable pulsars as yardsticks across cosmic distances. A passing gravitational wave would distort, over months and years, the timebase recorded from each. While individual pulsars may alter their behavior slightly due to local circumstances, a gravitational wave would act in concert on multiple sightlines, producing correlated advances and delays in the beat of their rhythms.

As the consortium has expanded and more telescopes provided more simultaneous sightlines to remote pulsars, the effective sensitivity of NANOGrav has increased. The longer it operates, as well, the better it can detect the longest-period gravitational waves. The Wednesday announcement is only the opening salvo in its work, an announcement, confident, at roughly the 999 out of 1,000 level, of detecting this universal background of waves.

The expansion of astronomical work from visible light to other frequencies opened new windows onto the phenomena of the Universe. The entire electromagnetic spectrum, from gamma waves at high frequencies to radio waves at low frequencies, is the target of specialized observatories. And just as with visible light, the opening of gravitational wave astronomy to greater frequencies will also enlarge the scope of its scientific reach.

Prospects

Over the coming years, it is planned that NANOGrav’s work will move from detection to characterization and the production of a “spectrum” of the intensity of waves over a range of their lengths, from which the growing body of information on supermassive black holes can be contrasted. And as with all new experimental endeavors, there will be careful examination for surprises. If, for instance, the dark matter that comprises substantially more of the Universe than its visible counterpart exists in “clumps” and a clump would happen to pass by a cluster of sightlines, it would be detected. If exotic objects such as “cosmic strings” exist, which some extensions to our physical theories permit, their signature might be detected. And other gravitational wave observatories are being planned to bridge the immense gap between the low frequencies recorded by NANOGrav and the high frequencies recorded by LIGO.

For all the sophistication and refinements in technique since Galileo, he would have recognized NANOGrav (and LIGO) as examples of his dictum quoted at the start of this article: “Count what is countable, measure what is measurable, and what is not measurable, make measurable.” From the correspondence of experiment with theory, confidence is gained in theory. And where experiment and theory differ, signposts to the refinement of theory are provided, which themselves feed back into refinements in technique.