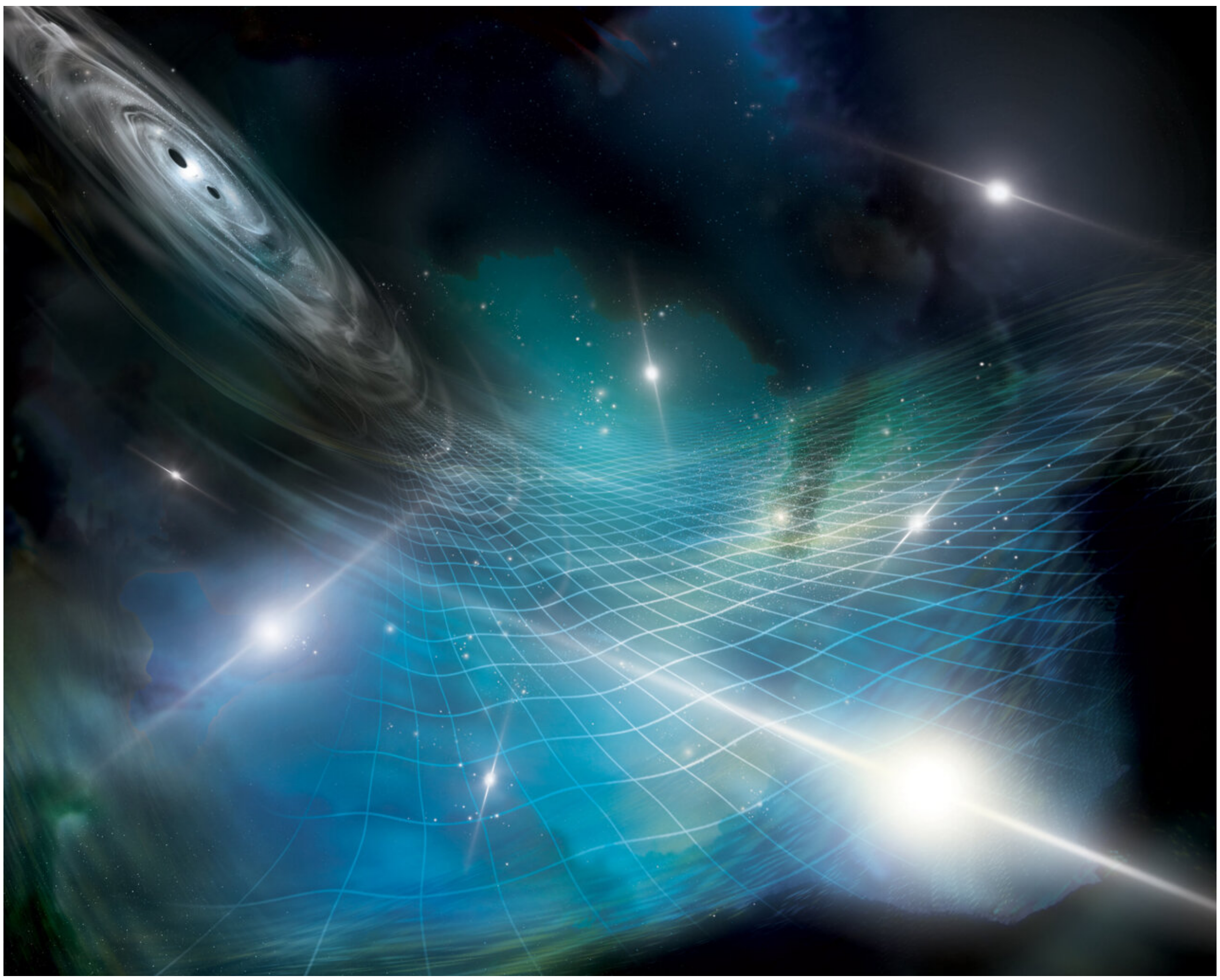
After 15 years, pulsar timing yields evidence of cosmic background gravitational waves

August 9 2023, by Robert Sanders



Artist's interpretation of an array of pulsarsbeing affected by gravitational ripples producedby a supermassive black hole binary in a distantgalaxy. Credit: Aurore Simonnet for the NANOGrav Collaboration

The universe is humming with gravitational radiation—a very low-frequency rumble that rhythmically stretches and compresses spacetime and the matter embedded in it.

That is the conclusion of several groups of researchers from around the world who simultaneously published a slew of journal articles in June describing more than 15 years of observations of millisecond pulsars within our corner of the Milky Way galaxy. At least one group—the North American Nanohertz Observatory for Gravitational Waves (NANOGrav) collaboration—has found compelling evidence that the precise rhythms of these pulsars are affected by the stretching and squeezing of spacetime by these long-wavelength gravitational waves.

"This is key evidence for gravitational waves at very low frequencies," says Vanderbilt University's Stephen Taylor, who co-led the search and is the current chair of the collaboration. "After years of work, NANOGrav is opening an entirely new window on the gravitational-wave universe."

Gravitational waves were first detected by the Laser Interferometer Gravitational-Wave Observatory (LIGO) in 2015. The short-wavelength fluctuations in spacetime were caused by the merger of smaller black holes, or occasionally neutron stars, all of them weighing in at less than a few hundred solar masses.

The question now is: Are the long-wavelength gravitational waves—with periods from years to decades—also produced by black holes?

In one paper from the NANOGrav consortium, published in *The Astrophysical Journal Letters*, University of California, Berkeley, physicist Luke Zoltan Kelley and the NANOGrav team argued that the hum is likely produced by hundreds of thousands of pairs of supermassive black holes—each weighing billions of times the mass of our sun—that over the history of the universe have gotten close enough to one another to merge.

The team produced simulations of supermassive black hole binary populations containing billions of sources and compared the predicted gravitational wave signatures with NANOGrav's most recent observations.

The black holes' orbital dance prior to merging vibrates spacetime analogous to the way waltzing dancers rhythmically vibrate a dance floor. Such mergers over the 13.8-billion-year age of the universe produced gravitational waves that today overlap, like the ripples from a handful of pebbles tossed into a pond, to produce the background hum. Because the wavelengths of these gravitational waves are measured in light years, detecting them required a galaxy-sized array of antennas—a collection of millisecond pulsars.

"I guess the elephant in the room is we're still not 100% sure that it's produced by supermassive black hole binaries. That is definitely our best guess, and it's fully consistent with the data, but we're not positive," said Kelley, UC Berkeley assistant adjunct professor of astronomy. "If it is binaries, then that's the first time that we've actually confirmed that supermassive black hole binaries exist, which has been a huge puzzle for more than 50 years now."

"The signal we're seeing is from a cosmological population over space and over time, in 3D. A collection of many, many of these binaries collectively give us this background," said astrophysicist Chung-Pei Ma, the Judy Chandler Webb Professor in the Physical Sciences in the departments of astronomy and physics at UC Berkeley and a member of the NANOGrav collaboration.

Ma noted that while astronomers have identified a number of possible supermassive black hole binaries using radio, optical and X-ray observations, they can use gravitational waves as a new siren to guide them where in the sky to search for electromagnetic waves and conduct detailed studies of black hole binaries.

Ma directs a project to study 100 of the closest supermassive black holes to Earth and is eager to find evidence of activity around one of them that suggests a binary pair so that NANOGrav can tune the pulsar timing array to probe that patch of the sky for gravitational waves. Supermassive black hole binaries likely emit gravitational waves for a couple of million years before they merge.

Other possible causes of the background gravitational waves include dark matter axions, black holes left over from the beginning of the universe—so-called primordial black holes—and cosmic strings. Another NANOGrav paper appearing in *ApJ Letters* lays out constraints on these theories.

"Other groups have suggested that this comes from cosmic inflation or cosmic strings or other kinds of new physical processes which themselves are very exciting, but we think binaries are much more likely. To really be able to definitively say that this is coming from binaries, however, what we have to do is measure how much the gravitational wave signal varies across the sky. Binaries should produce far larger variations than alternative sources," Kelley said.

"Now is really when the serious work and the excitement get started as we continue to build sensitivity. As we continue to make better measurements, our constraints on the supermassive black hole binary populations are just rapidly going to get better and better."

Galaxy mergers lead to black hole mergers

Most large galaxies are thought to have massive black holes at their centers, though they're hard to detect because the light they emit—ranging from X-rays to radio waves produced when stars and gas fall into the black hole—is typically blocked by surrounding gas and dust. Ma recently analyzed the motion of stars around the center of one large galaxy, M87, and refined estimates of its mass—5.37 billion times the mass of the sun—even though the black hole itself is totally obscured.

Tantalizingly, the supermassive black hole at the center of M87 could be a binary black hole. But no one knows for sure.

"My question for M87, or even our galactic center, Sagittarius A*, is: Can you hide a second black hole near the main black hole we've been studying? And I think currently no one can rule that out," Ma said. "The smoking gun for this detection of gravitational waves being from binary supermassive black holes would have to come from future studies, where we hope to be able to see continuous wave detections from single binary sources."

Simulations of galaxy mergers suggest that binary supermassive black holes are common, since the central black holes of two merging galaxies should sink together toward the center of the larger merged galaxy. These black holes would begin to orbit one another, though the waves that NANOGrav can detect are only emitted when they get very close, Kelley said—something like 10 to 100 times the diameter of our solar system, or 1,000 to 10,000 times the Earth-sun distance, which is 93 million miles.

But can interactions with gas and dust in the merged galaxy make the black holes spiral inward to get that close, making a merger inevitable?

"This has kind of been the biggest uncertainty in supermassive black hole binaries: How do you get them from just after galaxy merger down to where they're actually coalescing," Kelley said. "Galaxy mergers bring the two supermassive black holes together to about a kiloparsec or so—a distance of 3,200 light years, roughly the size of the nucleus of a galaxy. But they need to get down to five or six orders of magnitude smaller separations before they can actually produce gravitational waves."

"It could be that the two could just be stalled," Ma noted. "We call that the last parsec problem. If you had no other channel to shrink them, then we would not expect to see gravitational waves."

But the NANOGrav data suggest that most supermassive black hole binaries don't stall.

"The amplitude of the gravitational waves that we're seeing suggests that mergers are pretty effective, which means that a large fraction of supermassive black hole binaries are able to go from these large galaxy merger scales down to the very, very small subparsec scales," Kelley said.

NANOGrav was able to measure the background gravitational waves, thanks to the presence of millisecond pulsars—rapidly rotating neutron stars that sweep a bright beam of radio waves past Earth several hundred times per second. For unknown reasons, their pulsation rate is precise to within tenths of milliseconds.

When the first such millisecond pulsar was found in 1982 by the late UC Berkeley astronomer Donald Backer, he quickly realized that these precision flashers could be used to detect the spacetime fluctuations produced by gravitational waves. He coined the term "pulsar timing array" to describe a set of pulsars scattered around us in the galaxy that could be used as a detector.

In 2007, Backer was one of the founders of NANOGrav, a collaboration that now involves more than 190 scientists from the U.S. and Canada. The plan was to monitor at least once each month a group of millisecond pulsars in our portion of the Milky Way galaxy and, after accounting for the effects of motion, look for correlated changes in the pulse rates that could be ascribed to long-wavelength gravitational waves traveling through the galaxy. The change in arrival time of a particular pulsar signal would be on the order of a millionth of a second, Kelley said.

"It's only the statistically coherent variations that really are the hallmark of gravitational waves," he said. "You see variations on millisecond, tens of millisecond scales all the time. That's just due to noise processes. But you need to dig deep down through that and look at these correlations to pick up signals that have amplitudes of about 100 nanoseconds or so."

The NANOGrav collaboration monitored 68 pulsars in all, some for 15 years, and employed 67 in the current analysis. The group publicly released their analysis programs, which are being used by groups in Europe (European Pulsar Timing Array), Australia (Parkes Pulsar Timing Array) and China (Chinese Pulsar Timing Array) to correlate signals from different, though sometimes overlapping, sets of pulsars than used by NANOGrav.

The NANOGrav data allow several other inferences about the population of supermassive black hole binary mergers over the history of the universe, Kelley said. For one, the amplitude of the signal implies that the population skews toward higher masses. While known supermassive black holes max out at about 20 billion solar masses, many of those that created the background may have been bigger, perhaps even 40 or 60 billion solar masses. Alternatively, there may just be many more supermassive black hole binaries than we think.

"While the observed amplitude of the gravitational wave signal is broadly consistent with our expectations, it's definitely a bit on the high side," he said. "So we need to have some combination of relatively massive supermassive black holes, a very high occurrence rate of those black holes, and they probably need to be able to coalesce quite effectively to be able to produce these amplitudes that we see. Or maybe it's more like the masses are 20% larger than we thought, but also they merge twice as effectively, or some combination of parameters."

As more data comes in from more years of observations, the NANOGrav team expects to get more convincing evidence for a cosmic gravitational wave background and what's producing it, which could be a combination of sources. For now, astronomers are excited about the prospects for gravitational wave astronomy.

"This is very exciting as a new tool," Ma said. "This opens up a completely new window for supermassive black hole studies."

NANOGrav's data came from 15 years of observations by the Arecibo Observatory in Puerto Rico, a facility that collapsed and became unusable in 2020; the Green Bank Telescope in West Virginia; and the Very Large Array in New Mexico. Future NANOGrav results will incorporate data from the Canadian Hydrogen Intensity Mapping Experiment (CHIME) radio telescope, which was added to the project in 2019.

More information: Gabriella Agazie et al, The NANOGrav 15 yr Data Set: Constraints on Supermassive Black Hole Binaries from the Gravitational-wave Background, *The Astrophysical Journal Letters* (2023). DOI: 10.3847/2041-8213/ace18b

Provided by University of California - Berkeley