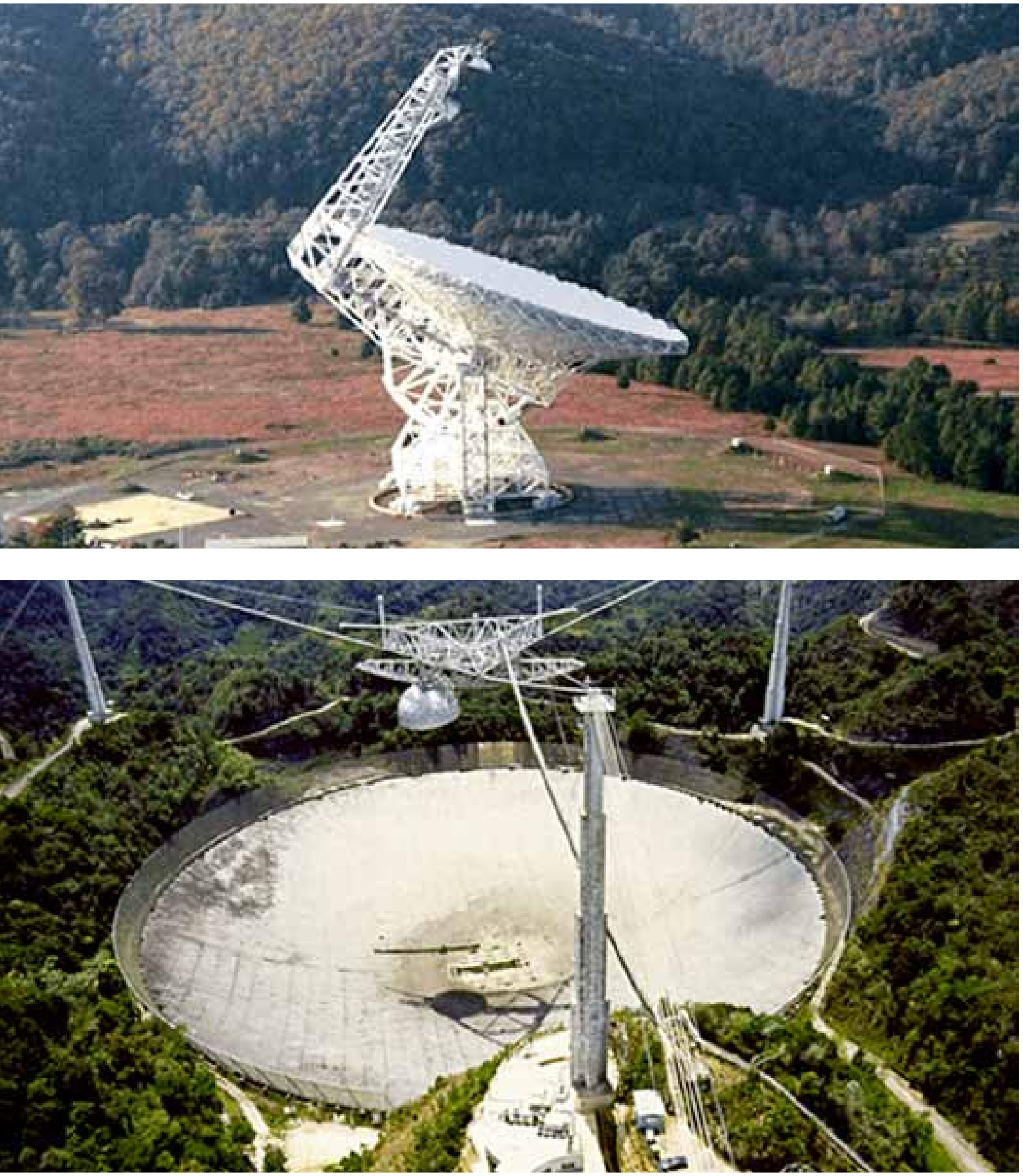
ASTRO ✦ BEAT



Catching Gravitational Waves with Radio Pulsars

By Timothy Dolch (Hillsdale College) May 2018

In the five decades since Jocelyn Bell-Burnell's discovery of the first pulsating radio star—a pulsar—we now know of at least 2600 such objects in our Galaxy. Many of these lighthouse-like interstellar beacons are active not only at radio wavelengths, but across the electromagnetic spectrum: for example, the Crab Pulsar emits about thirty flashes per second even in optical light. Short rotational periods, usually on the order of one second or less, constrain these energetic objects to have diameters of about 10 km. The only state of matter known to remain stable under such high centrifugal forces is nuclear matter. In other words, pulsars are enormous, rapidly rotating atomic nuclei! Such an exotic state of matter—known as a neutron star—is consistent with predictions that supernovae should leave compact remnants behind. The Crab pulsar is the Holy Grail of the supernova-neutron star connection; the pulsar sits right in the middle of the Crab Nebula, associated with the Crab Supernova of 1054.

Figure 1: The NRAO Robert C. Byrd Green Bank Telescope in West Virginia (top) and the 305-m William E. Gordon Telescope at Arecibo Observatory in Puerto Rico (bottom). From greenbankobservatory.org

The long-term monitoring of pulsars, referred to as "pulsar timing", has unveiled a myriad of astrophysical discoveries, including the first extrasolar planet and the first evidence of gravitational-wave emission. (Both discoveries were made with the Arecibo Observatory in Puerto Rico.) In the second case, the discoverers, Joseph Taylor and Russell Hulse, won the 1993 Nobel Prize in Physics for their observations of pulsar B1913+16 and its companion, also a neutron star. The system's orbital decay was astonishingly consistent with the emission of gravitational waves (GWs) as predicted by Einstein's theory of general relativity. Unlike light, GWs are waves in space itself, stretching and shrinking whatever structures occupy that space. While B1913+16 convinced physicists that GWs exist, the waves were, and still are, too weak to detect directly. Detecting any form of GWs remained elusive until 2015, when the Laser Interferometer Gravitational-wave Observatory (LIGO) detected the first GW burst from a merging black hole binary. At the time of this writing in 2018, the LIGO-Virgo Scientific Collaboration, including the Virgo detector in Italy, has announced five additional black hole mergers and one neutron star merger. The neutron star merger was accompanied by a flash in gamma rays, by a glow in optical light, and by dynamic emission across the rest of the electromagnetic (EM) spectrum, becoming the first "multimessenger" GW astronomy event. Just as Karl Jansky opened up a new sky when he detected radio emission from our Galaxy in 1933, the 1000+ scientists who work on LIGO have opened up the GW sky. The Nobel committee acknowledged this revolution when it awarded its 2017 physics prize to the LIGO pioneers Barry Barish, Kip Thorne, and Rainier Weiss.

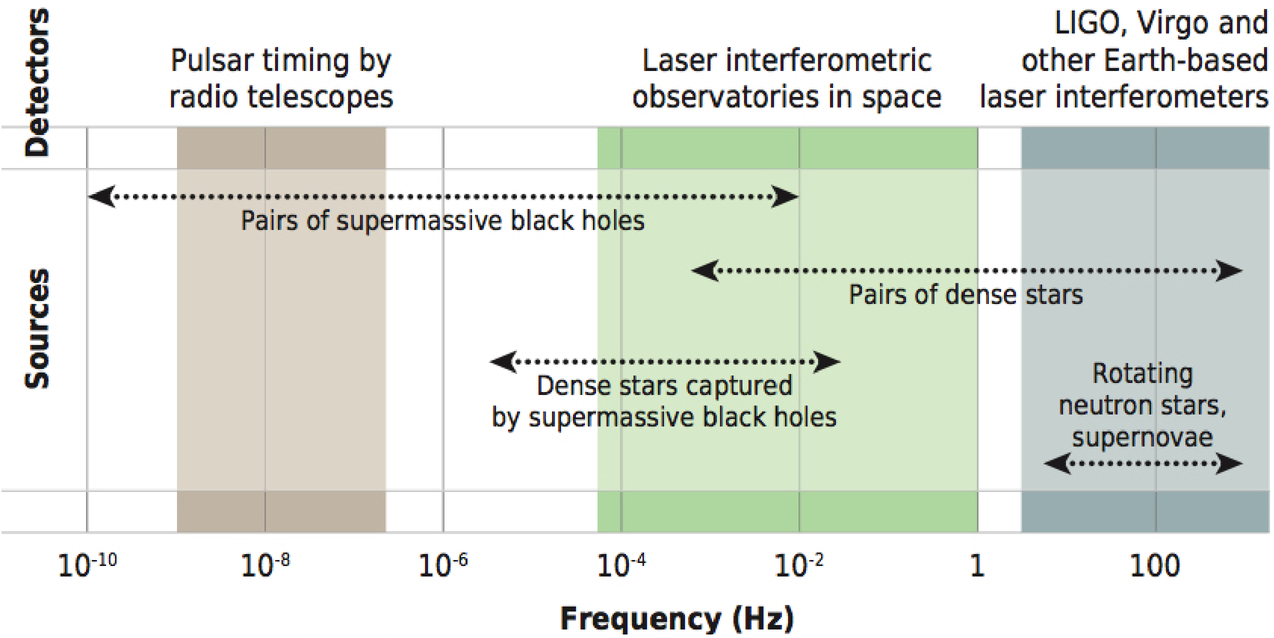


Figure 2: The gravitational wave spectrum. Frequencies are GW frequencies, not radio frequencies. (from Barke et al. 2015)

These black hole and neutron star mergers had GW frequencies in the 100s of Hz. But just as the EM spectrum is populated with different astrophysical phenomena at different EM wavelengths (stars in visible light; dust in infrared; pulsars and quasars in radio), the GW spectrum also sees radically different skies at different GW wavelengths. The Laser Interferometer Space Antenna (LISA) is like LIGO, but in space. This constellation of three satellites, to be launched in 2034, will see GWs with oscillation periods of hours. Theorists predict that LISA spectrum will be plentiful with sources. A proof-of-concept spacecraft called the LISA Pathfinder has successfully demonstrated the feasibility of a GW detector in space.

If we look to the even lower GW frequencies of around a nanohertz—which means GWs with *periods* of about a year!—we should see a sky blazing in every direction with pairs of supermassive black holes (SMBHs) undergoing mergers. While all black holes are unimaginably massive, SMBHs take the cake. (Quite literally if dropped into the event horizon.) At up to *billions* of times the mass of the sun, they reside in the centers of galaxies, as is the case with black hole Sagittarius A* in the center of the Milky Way. The astounding history of galaxy evolution that the Hubble Space Telescope has revealed to us—small galaxies merging together to form larger ones like our Milky Way—should mean that the largest black holes in each galaxy undergoing merger eventually find each other and merge as well. True, black holes can collect stars and gas indefinitely, because nothing that crosses into their event horizon can escape. Nevertheless, it is difficult to explain the existence of SMBHs without a history of black hole mergers following on the known history of galaxy mergers. All that remains is to catch a SMBH merger in the act.

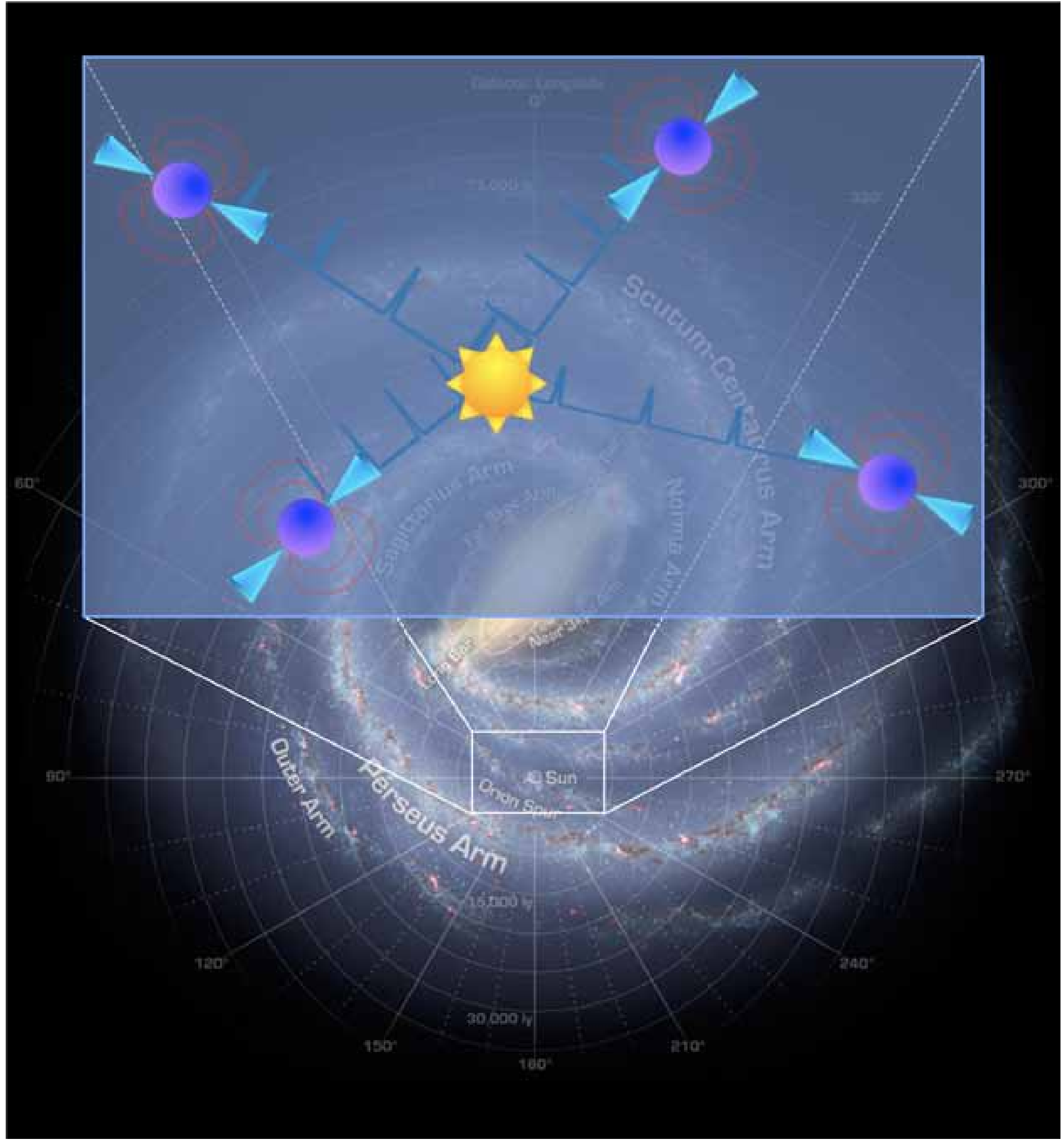


Figure 3: Illustration of lines-of-sight in our Galaxy to four of the 70+ pulsars used in NANOGrav for gravitational wave detection. Each line-of-sight, spanning thousands of light years, is like a detector arm of LIGO. Courtesy Jeffrey Hazboun / NASA / JPL-Caltech / R. Hurt (SSC-Caltech)

That brings us back to radio pulsars. In the late 1970s and early 1980s, several leading figures in the field—the theoretical astrophysicists Mikhail Sazhin and Steven Detweiler, and the radio astronomers Ron Hellings and George Downs at the Jet Propulsion Laboratory—noticed that nature had already given us a Galaxy-sized GW detector for free. If GWs stretch and shrink the fabric of spacetime, that means that the distances between a pulsar's radio pulses will change under their influence.

If space stretches, a particular pulsar will appear to slow down. If space shrinks, a pulsar will appear to speed up. If we therefore monitor the most regularly flashing pulsars in the sky, those pulsars function as a pulsar timing array (PTA)—the pulsars themselves become a GW telescope!

The fastest-spinning pulsars have periods on the order of a millisecond. The first millisecond pulsar (MSP) was detected in 1982, and since then, hundreds of these exotic objects have been discovered. MSPs are the best pulsars for GW detection. Long-term efforts to monitor many MSPs across the sky began in the early 2000s. Because we are searching for GWs with periods of a year or so, it has taken decade-timescales to build up enough time-of-arrival measurements so that several full GW oscillations will be present in the data. Here in North America, we use the Arecibo Observatory and the Greek Bank Telescope (GBT) in West Virginia to monitor more than 70 MSPs. The collaboration of radio astronomers, GW physicists, and students undertaking this project is called the North American Nanohertz Observatory for Gravitational Waves, or NANOGrav. (The NANOGrav Collaboration has recently become a National Science Foundation Physics Frontiers Center.) Now that we have been monitoring a large fraction of these pulsars for over a decade, we have just reached "first light", and expect a GW detection of SMBHs in the next few years.

This is all the more likely because two other groups are monitoring pulsars for the purpose of GW detection: the European Pulsar Timing Array collaboration, utilizing five radio telescopes, and the Parkes Pulsar Timing array collaboration in Australia, using the famous radio telescope of the same name. The three collaborations combine our data together to become the International Pulsar Timing Array.

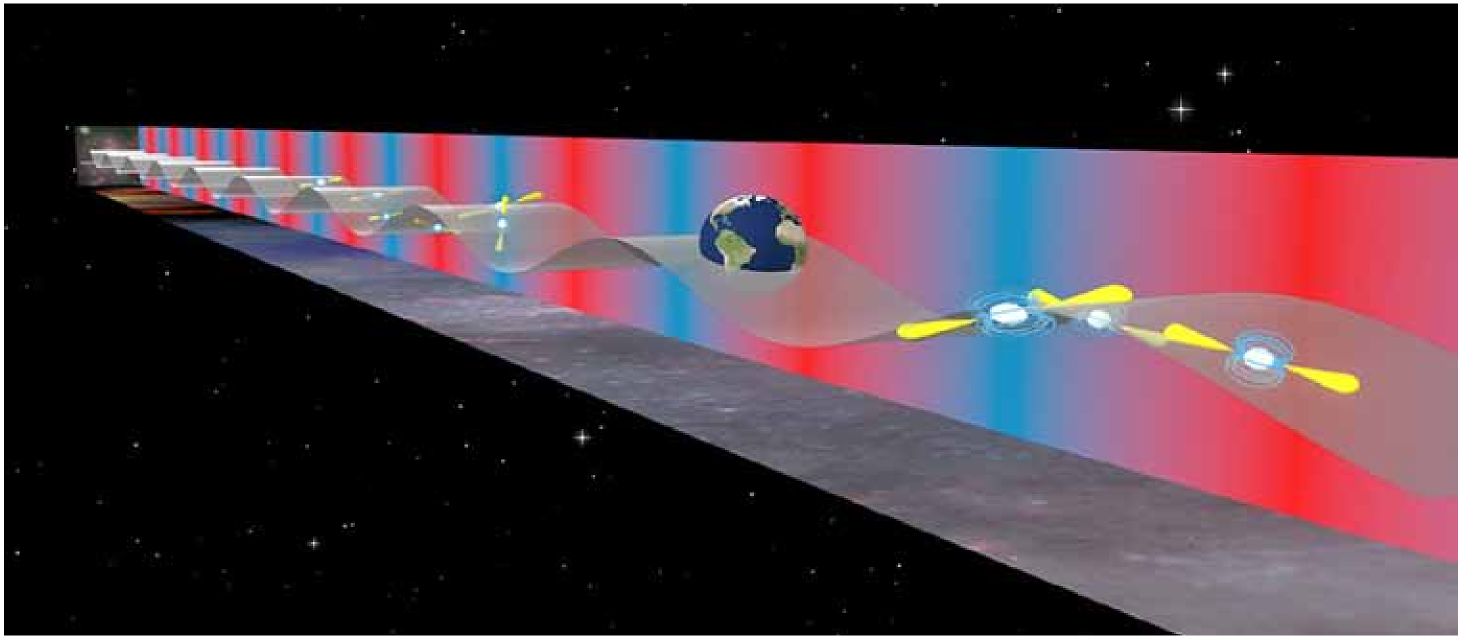
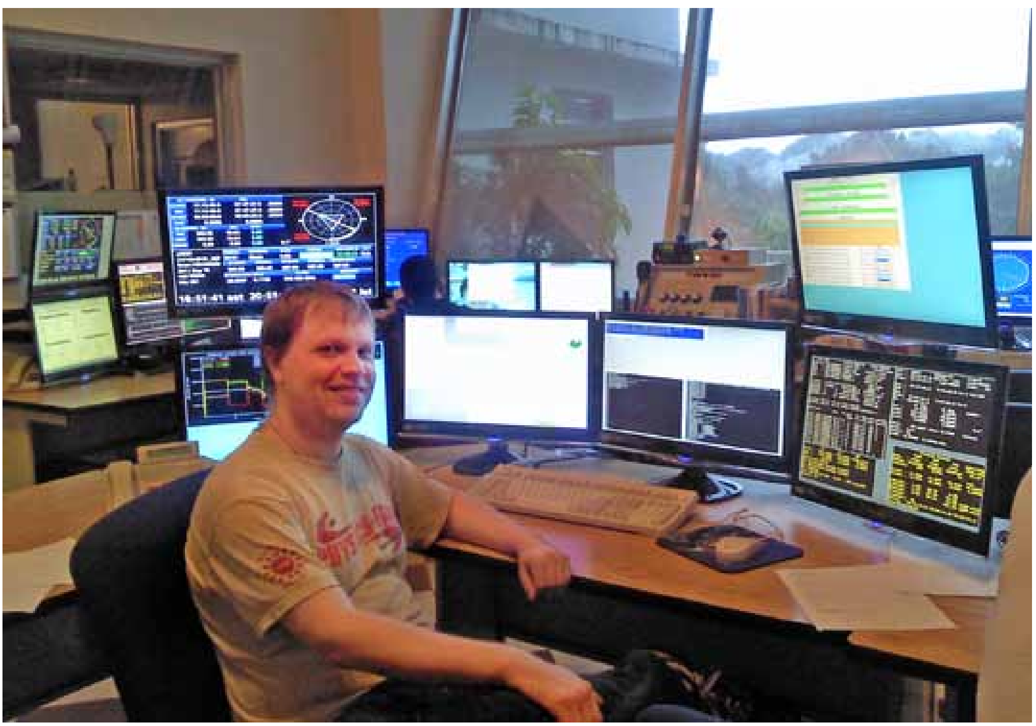


Figure 4: Continuous gravitational waves perturbing the positions of the earth and of several radio pulsars. Credit: B. Saxton (NRAO/AUI/NSF)

The GWs produced by merging SMBH binaries come in many flavors. Their most likely manifestation is a cosmological, all-sky background of GWs, coming from the numerous SMBH mergers that have happened in cosmic history in every direction in the sky. Just as the cosmic microwave background is a radio glow coming from every direction, so the GW background is a "glow" of GWs that should affect the pulse times-of-arrival from every pulsar in the array. While the prospect of detecting innumerable black holes simultaneously sounds daunting, in fact, such a background is probably the *easiest* manifestation of GWs to detect with PTAs. First, because the background should have a characteristic GW spectrum, strongest at lower frequencies. Second, because of the way that the background changes the received pulse periods is not random; signals from pulsar pairs near each other in the sky are stretched or shrunk together, whereas pulsar pairs in different sky directions get altered in an uncorrelated way. (Hellings and Downs predicted a very specific pattern of such correlations.) Because of the importance of comparing pulse arrival times from as many pairs of pulsars as possible, a critical part of the PTA effort is the ongoing discovery of new pulsars. The many fruitful pulsar searching projects have given PTAs about four new pulsars a year. Our GW telescope is always growing!



Timothy Dolch in Arecibo Observatory control room.

Currently, the absence of a GW background detection after 11 years of data has already led to some interesting astrophysical conclusions. The recently published analysis of the NANOGrav 11-year dataset shows that the centers of galaxies are likely to be more densely packed with stars than previously thought. It also shows that for SMBHs over cosmic history, the orbits around one another are likely to be more elliptical than previously thought.

Galaxies and their supermassive black holes have merged; therefore, a GW background must exist. Additionally, several other extragalactic GW phenomena should eventually show up in pulsar data.

Continuous Waves

The GW background is a sum of GWs from the "cruising" phase of mergers: the black holes are gradually spiraling nearer and nearer to one another but are nowhere near the cataclysmic moment when they become one. (That moment creates a sudden burst of GWs, such as the five bursts that LIGO has seen.) Each individual system in the cruising phase emits so-called "continuous waves", which is to say, a simple sine-wave oscillation in spacetime. If a particular SMBH binary in this continuous-wave scenario is near enough to us and/or bright enough, a particular sine wave-like signal should show up in pulse times-of-arrival. NANOGrav is currently planning a multimessenger effort similar to the network of EM telescopes that followed up the LIGO neutron star merger. Should such a continuous wave signal emerge in GW data, the particular galaxy in which the SMBHs are merging could be located by finding periodic optical and/or high energy periodic variability in a distant galaxy's center. Conversely, should a bright enough candidate black hole pair be discovered optically, pulsar-timing data could be searched for GW signals at the predicted frequency and in the predicted sky-direction.

Bursts

The moment of black hole merger, in addition to creating the bursts that LIGO-Virgo detected, also creates an unusual burst of waves called a memory burst. A memory burst is a sudden, one-time stretch in the fabric of space time that would result in a one-time period change of many pulsars in the sky. A period increase means that the discrepancy between predicted and actual pulsar arrival times would build up after the event, and so PTAs are the best tool for finding memory bursts. Other burst events might be detectable as well, such as SMBH binaries in highly elliptical orbits that suddenly veer around each other.

New Physics

The early decades of radio astronomy were the story of unanticipated objects. Quasars, for example, were "radio stars" (quasi-stellar objects) that much later turned out to be distant galaxies with SMBH-powered high-velocity jets. Similarly, the most interesting objects in the GW sky may be the least expected. If such objects are entirely unanticipated, we will only have to wait! But when theorists use their imaginations, several possibilities are at the top of the list. First, cosmic strings, which are one-dimensional discontinuities in space-time left over from the formation of the universe (much like the cracks that form in melting ice) should produce GWs when they form loops. Second, some models of the ever-elusive but ever-present substance we call "dark matter" should make an imprint on pulsar timing data. Third, relic GWs should be left over from the early, inflationary era of the universe. Currently, PTAs are the most sensitive tool to search for such relic waves, as the recent NANOGrav 11-year analysis has shown.

The biggest question about pulsar timing arrays remains: when will we detect GWs? Many statistical irregularities—in other words "noise"—lurk in pulsar timing, just as LIGO was able to pick up tiny, distant acoustic vibrations. In the 11-year NANOGrav data release, the most prominent source of such "noise" is the tiny spatial wandering of our solar system itself. However, like all uncertainties in pulsar timing, this particular source of noise will likely get better with time. The strongest concern is in the realm of policy rather than science: the uncertain future of our telescopes, in particular, of the Arecibo Observatory. The iconic telescope, well-known from the movies Contact and James Bond: Goldeneye, will be federally funded for the next five years, but at a rate that gradually decreases to zero with the expectation that private sources of funding will make up the difference. If a long-term funding model fails to materialize at the end of these five years, we will have effectively shut down a GW detector at the very moment when the era of GW astronomy has been inaugurated. It would be a particularly sad tragedy, given that PTAs are the one GW detection method that requires no new facility, and that our long-term pulsar searching and timing campaigns yield an abundance of bonus science about neutron stars and their environments. Finally, pulsar timing is a field in which undergraduate students make a unique impact. Pulsar searching and observing are routinely performed by undergraduate students. At many of our institutions, for example here at Hillsdale College, students remotely control both the GBT and the Arecibo Observatory. Many pulsars were originally discovered by NANOGrav students, which means that our GW detector is partially student-built.

Despite an uncertain long-term telescope future, we in the pulsar timing array community remain optimistic that nature will continue to surprise us with the wonders of neutron stars—as it has for the last fifty years without any hint of taking a break!

Acronym Glossary:

EM: electromagnetic spectrum
GBT: Greek Bank Telescope
GW(s): gravitational wave(s)
LIGO: Laser Interferometer Gravitational-wave Observatory
LISA: Laser Interferometer Space Antenna
MSP(s): millisecond pulsar(s)
NANOGrav: North American Nanohertz Observatory for Gravitational Waves
NRAO: National Radio Astronomy Observatory
PTA(s): pulsar timing array(s)
SMBH(s): supermassive black hole(s)

About the Author

Timothy Dolch is an assistant professor of physics at Hillsdale College in Michigan and a member of North American Nanohertz Observatory for Gravitational Waves (NANOGrav) and the International Pulsar Timing Array collaborations. Within NANOGrav, his research focus is on the

interaction of pulsars with the interstellar medium. Recently he has been involved with optical observations of the nebulae surrounding pulsars. (The picture is from the elevator at the Mayall Telescope at Kitt Peak National Observatory.) He has a BS in physics from the California Institute of Technology, and a PhD in Physics and Astronomy from the Johns Hopkins University.

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