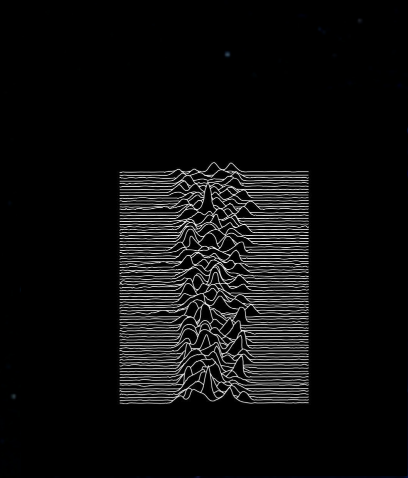
Pulsars

MANCHESTER
1824
The University of Manchester

Tutorial Group 29

Introduction

Pulsars are an important tool in an astronomers arsenal. Rapidly rotating neutron stars which emit beams of radiation are a fascinating phenomena, made more so by how useful they are for testing our theories of nature. From confirming general relativity, to helping us study the interstellar medium, these cosmic lighthouses are of striking importance to science. However, there is still a lot we can learn about pulsars themselves, with new research continuously being done on the topic, and with astronomers always searching for and mapping new pulsars in our galaxy and beyond.



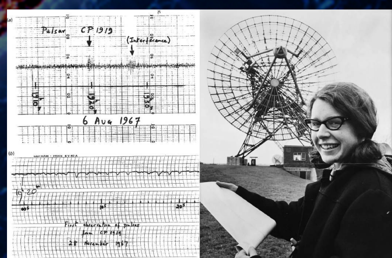
Recordings from CP1919 visualised and stacked. The rendition shown in the figure is one used on the Joy Division album, "Unknown Pleasures".

In this booklet, we will present to you a deep but accessible view at pulsars. We will present the science behind how they work and why, and how they are currently being used in the frontiers of science. First, we'll begin with how the first pulsar was discovered.

Discovery of Pulsars

The first pulsar was discovered by Jocelyn Bell Burnell, a PhD student at Cambridge university, in 1967. At the time, she had been investigating the radio scintillations of quasars, highly luminous accretion disks of black holes[1][2]. However, among the expected data she had observed a series of consistent radio pulses, occurring every 1.33 seconds[3]. Bell had been assigned to analyse all the large amounts of data from the telescope by hand every day, lending to her proficiency in determining the difference between genuine sources and generic man made interference. This type of behaviour was highly unusual for any celestial object at the time. This led to Bell and her supervisor, Anthony Hewish, to posit that the signals may have come from an extraterrestrial civilization. This led to the source being nicknamed "LGM-1", for "little green men"[4].

Bell had later made a comment on the "Little Green Men" after detecting another similar frequency from another part of the sky; "It was highly unlikely that two lots of Little Green Men could choose the same unusual frequency and unlikely technique to signal to the same inconspicuous planet Earth!". Thus, alien communication idea was quickly ruled out, while she began to find more objects of similar behaviour, totalling to 4 by the end of December 1967. The discovery paper [5], included LGM-1 (now known as CP1919, for Cambridge pulsar at 19 hours 19 minutes right ascension), although they had yet to work out what they actually were. The discovery paper posited that the pulses were due to vibrating neutron stars, though this was only an educated guess.



Jocelyn Bell and the first pulsar detection. (Cavendish Laboratory)

The debate was settled in with the discovery of the crab nebula, when the time derivative of the pulsar period was measured and was found to be positive. This indicated that the period of the pulsar was slowing down, indicative of a rotating system. Thomas Gold was the one to publish this finding, as well as formalising the main properties of pulsars[6]. Physicists finally had an answer to "What is a pulsar?".

What are Pulsars?

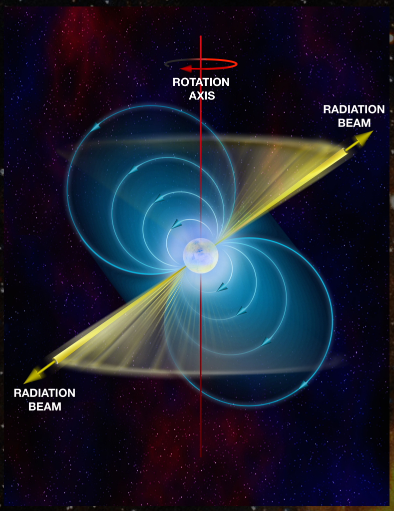


Fig. 1 Pulsars emit radio signals due to electrons travelling at extremely relativistic speeds along the magnetic field lines at the poles of the pulsar. As these electrons accelerate, they emit electromagnetic radiation, allowing for us to detect the signals on Earth. (B. Saxton, NRAO/AUI/NSF)

The question we must ask first is, what is a neutron star? A neutron star is formed a supergiant star collapses and undergoes supernova. Once the star runs out of fuel, nuclear fusion ceases and the star begins to cool. At this point the core of the star has undergone fusion to become iron. The reduced temperature of the star causes the pressure inside it to decrease and so gravity begins to pull it inward. The shrinking of the star causes the interior to heat up again and half of the generated heat flows outward to the star's surface, where it is radiated away into space[7].

Without the pressure of the hot gas there is one main force. This is the electron degeneracy pressure. This occurs when electrons are compressed into a very small volume. The density required for electron degeneracy is approximately 10×10^6kgm^3 which is more than 100 times the density of steel.

For a star with a mass close to that of our sun, the electron degeneracy pressure would be in equilibrium with the gravitational forces however in the case of a very massive star, gravity overcomes the electron degeneracy pressure which causes the star to collapse even further. This causes the star to approach the Chandrasekhar limit of $\rho = 10^9$kgm^{-3}, at which point the electrons become relativistic. This means that they have enough energy to be forced into the iron nuclei in the star's core, and they merge with protons to form neutrons, and emitting electron neutrinos in the process. [1]

This process continues until all the mass of the star has been converted into neutrons, leading to a star composed entirely of neutrons. In addition to their fascinating composition, neutron stars are extremely dense; a neutron star of 1.4 solar masses will have a diameter of 20 kilometers - less than the size of Manchester! If you were to take just a teaspoon of a neutron star, its mass would be of the order of a trillion kilograms!

Pulsars are rapidly rotating neutron stars which emit radiation, which we usually detect in the form of radiowaves, although pulsars can emit over the entire range of the electromagnetic spectrum, including x-ray and visible light. They are able to do this due to having extremely strong magnetic fields, with the most magnetic pulsar discovered yet being around 1.6×10^{13}G[8] (for reference, the Earth has a magnetic field of around 0.25-0.65G). Electrons are accelerated to highly relativistic speeds along the magnetic field lines of the pulsar, causing them to emit radiation due to disturbance in their electric field. We are then able to detect these beams of radiation as they sweep across the universe and onto our planet Earth, similar to the beams of a lighthouse (see figure 1).

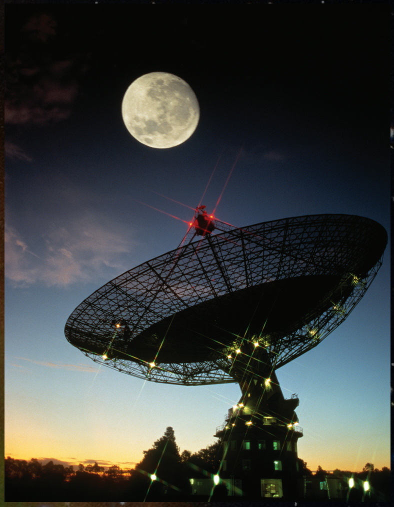
We mentioned that pulsars spin rapidly - and indeed, most pulsars have periods ranging from milliseconds to tens of seconds. The longest measured period was one of 75.9 seconds [9] and the shortest period being about 1.4 milliseconds[10]. These are astounding numbers, especially when considering the precision of these pulses, with the period only changing by $10^{-12} - 10^{-21}$ seconds per second[3], rivalling that of atomic clocks. They do this to maintain the angular momentum of the star they were formed from.

The unique and fascinating properties of pulsars make them very interesting objects for scientists to find and observe. In the following sections, we outline how physicists find and observe pulsars, and how they use their findings in the frontiers of physics.

Pulsar Detection

Since 1967, over 2000 pulsars have been detected, most of which within our plane of the Milky Way. A large proportion of these have been found using the CSIRO's Parkes radio telescope – finding double compared to the rest of the world's telescopes combined. [11]

How are these pulses found? A radio telescope will be pointed towards a specific part of the sky over a period which could range from a few minutes to 12 hours, the longer times allowing for weaker pulse detection[11]. Readings are taken continuously and then data analysed for patterns by computers, rather than by hand like Bell did in the past. To conceptualise the pattern, graphs can be drawn, or you can plug the data into a speaker to hear the signal!



CSRIO's Parke's telescope (Seth Shostak).

Pulsar observations are not confined to just the pulse period, but can highlight further properties of each individual one. Each pulse is made up of a spectrum of different wavelengths of radio waves, and therefore as they travel through space, they experience dispersion. Due to free electrons in the space between the pulsar and Earth, higher frequency waves arrive slightly before the lower ones. As further away pulsar signals must travel through more space, they experience more dispersion and so the time difference in frequencies can help to predict their distance from Earth. X-ray detection from pulsars can be used to determine more information about them, since the properties of the X-rays emitted are highly dependent on their age[12]. For example, older pulsars have X-ray pulses that are far broader than that of young ones, which release in short bursts due to the acceleration of charged particles in its magnetosphere.

Even more can be found if the pulsar is in orbit with another stellar object (a binary system). Looking at their motion as a pair can help to estimate pulsar mass - approximately 1.5 times the Sun's mass – and so its (very high) density. Conversely, the pulsar can be used to find the mass of the other object in the system, using the 'Shapiro delay' between signal arrival times[13]. This delay is a result of the idea that radio waves passing by a massive object are distorted by its gravity. Hence if the pulsar is paired in orbit with a large star, its pulses will curve. From an observational perspective, this causes the radio waves to take longer to arrive when the large star is in front of the pulsar. Shapiro delay and binary systems are further covered in the "Application of Pulsar Astronomy" section.

Future Pulsar Detection

Despite the progress in detection of pulsars over the past decades, there is still a significant amount we do not know about; new equipment is hence being made in order to further this research. One such project is the Square Kilometre Array (SKA), which has hopes to find not only thousands more pulsars but also the first galactic centre and extragalactic ones[14]. But what is the SKA?

The SKA is a series of hundreds of antennae and dishes working in tandem to become the two highly advanced radio telescopes, located in Australia (the 'SKA-Low') and South America (the 'SKA-Mid')[15]. Both locations are in the southern hemisphere since they have the best viewpoint into the Milky Way and further into space[16].

Such a large scale project is required to reach the distances and accuracies desired, since for the same research a single telescope of a collecting area around one square kilometre would be needed. Rather than a singular huge telescope, the SKA-Low and SKA-Mid act as interferometers [16] – a combination of multiple smaller telescopes acting as one.

Such research includes the early Universe, galaxy evolution, astrobiology and of course pulsars[17]. Specifically with pulsars, they look to find precise timing measurements for the radio pulses, and from this extract gravitational wave data [18] that could contribute to studies in space and time itself.

Artist impression of the Square Kilometre Array telescope. (SKAO)

Application of Pulsar Astronomy

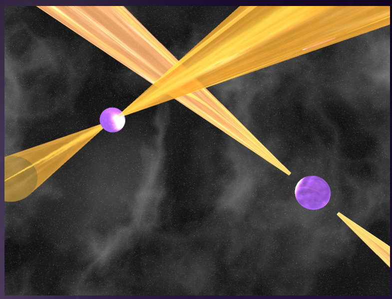
Pulsars have helped us achieve many scientific breakthroughs, such as the measurement of gravitational waves, giving us insight into the nature of the early Universe, to helping confirm Einstein's general relativity. Below, we outline these breakthrough's and the science that was used to achieve them.

Testing General Relativity

Binary pulsars allow us to test general relativity. These are systems which consist of a pulsar in a binary orbit with another star, such as a neutron star or white dwarf. The strong gravitational fields produced by these systems are of particular importance to scientists, and allow them to test Einstein's theories.

In 2003 scientists discovered the only known binary pulsar system – PSR J0737-3039A/B. What makes this system ideal for observations is that it is only around two thousand light years away from

Earth, and its inclination is very close to 90 with the plane of the sky[19]. Professor Michael Kramer and his team at the Jodrell Bank Observatory used three years of observations from this double pulsar to test general relativity using several methods, outlined on the following pages.



Artist's impression of binary pulsar PSR J0737-3039. (Michael Kramer, Jodrell Bank Observatory, University of Manchester).

Gravitational Redshift

The extremely dense pulsars cause each other to undergo gravitational time dilation – causing their pulse rates to slow when they get close to one another - this is known as Gravitational redshift. Gravitational redshift also has to be accounted for when you are collecting data from a pulsar. As gravitational waves pass through our galaxy this causes a redshift in the frequency of the pulses as measured on Earth. [20]

Shapiro delay

The test that gives the most precise result is measuring the phenomenon of Shapiro delay. This is when the curved spacetime around the pulsars causes the pulse emitted from one to slow down as it passes the other - as predicted by general relativity. For the double pulsar, this delay was measured to be around 90 millionths of a second to a precision level of 0.05%. [20]

Gravitational Radiation

Observations of PSR J0737-3039A/B showed that over time, the orbital radius was decreasing whilst the rate of revolution was increasing. Their separation distance was measured to be shrinking by around 7 millimetres every day. This was evidence to show that the system loses orbital energy as it radiates gravitational waves, causing the neutron stars to begin to spiral in towards each other. Gravitational waves are predicted by Einstein's theory of relativity, and whilst before 2015 they had not been detected directly, these observations are indirect proof that they exist. [20]

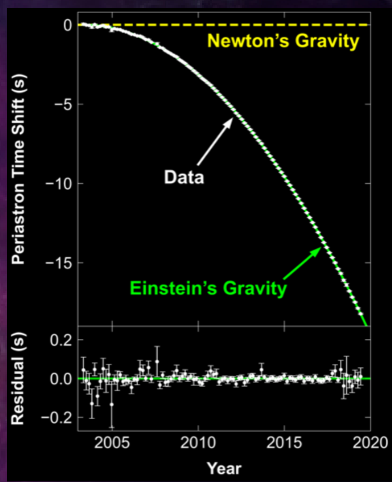


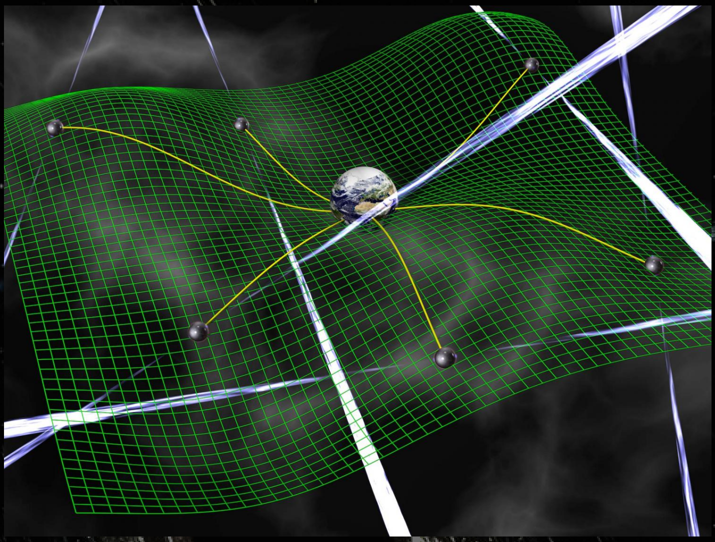
Fig. 2 Data from continued observation of the double pulsar systek collected over 16 years (APS/L. Shao).

Figure 2 [21] uses data from continued observations of the double pulsar, collected over 16 years. It shows the cumulative periastron time shift - the time between when the two stars are at their closest to one another. The graph shows that over the years this time is decreasing, demonstrating the increased rotational speed of the pulsars due to gravitational radiation. The graph also shows what Newton's theory and Einstein's theory of general relativity would predict these results to be. As you can see, the data matches almost perfectly to Einstein's theory. In fact, it agrees with the data to a level of 1.3×10^{-4} with 95% confidence. [19]

Gravitational Wave Measurement

Gravitational waves were first suggested by English physicist Oliver Heaviside in 1893 [22] when comparing the similarities of the inverse square law of both electricity and gravity, and would later be elaborated on by Albert Einstein in 1916 in his theory of general relativity [20], as ripples in space time due to the movement of masses bending it, propagating at the greatest possible speed for any natural interaction, the speed of light.

In practice, this results in space being contracted on one axis while being stretched on a perpendicular axis, and then being stretched on the perpendicular axis and contracted on the other, as the peaks a troughs of the gravitational wave pass through the space [23]. This was first directly measured in 2016 by the Laser Interferometer Gravitational-Wave Observatory (LIGO) in Louisiana [24], capable of measuring of less than 1/10,000th the diameter of a proton, relying on two 4km detectors placed to each other to measure gravitational waves from colliding black holes.



Graviational waves cause spacetime (shown in green) to ripple. Pulsars help detect low frequency ripples, as it causes the radio signals emitted from them to take longer to travel to Earth (David Champion).

While its possible to observe short gravitational waves through apparatus such as LIGO, for longer gravitational waves, like the ones produced by the Supermassive black holes (SMBH) at the centres of galaxies, with wavelengths of several light years, the contraction and expansion of spacetime must be measured over a much greater distance than the 4km of LIGO.

Astronomers have turned to the incredibly accurate time measurement properties of pulsars in order to calculate their distance from earth, and thus use them as much longer versions of LIGOs 4km arms. Due to the consistent nature of Millisecond Pulsar rotation, and consistent speed of light, the distance between the pulsar and earth can simply be calculated as the product of the speed of light, and the time said light spent travelling to earth, the time in this case measured by the pulsar rotation observed by radio telescopes on earth.

However, since individual pulsars can speed up or down in rotational speed, and also ionised gas can slow down the radio light, instead of observing individual pulsars, up to 100 [25] are grouped into Pulsar Timing Arrays (PTA) [23], thus any factor effecting a particular pulsar, or even a group of pulsars in a particular region, can be distinguished from gravitational waves, which by their very nature will effect spacetime from all pulsars in a correlated way, creating a minuscule, but measurable time difference from the expected period of the pulsar, called a Pulsar Timing Residual (PTR).

The correlation of PTRs have also brought astronomers close to confirming the long suspected stochastic gravitational background radiation[26]. As previously mentioned, gravitational waves stretch and contract spacetime at a right angles, and thus and expected correlation of PTRs at different relative angles can be established, given by the Hellings-Downs Curve [27], where pulsars with a relative angle close to 0 degrees and 180 degrees have a positive correlation, and those close to 90 degrees have an anti correlation, as they are impacted by gravitational waves on a different axis.

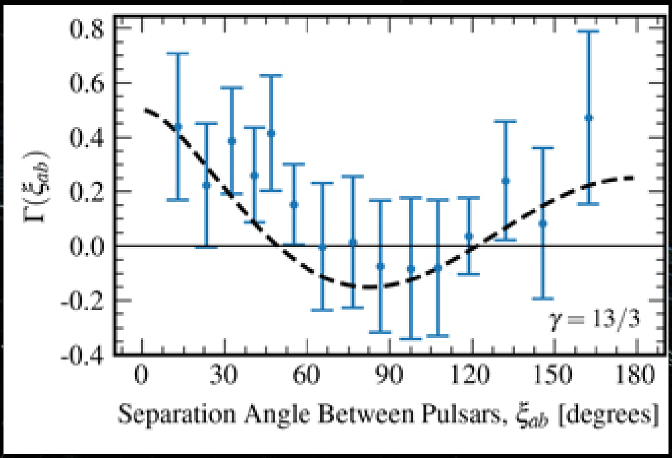


Fig. 3 A Hellings-Down Curve overlaid overlaid with data collected by the NANOGrav over the last 15 years.

Figure 3 is the the Hellings-Downs Curve, which is a function of the angles of Earth-pulsar baselines, overlaid with data collected by the NANOGrav PTA over the last 15 years [28], which shows promisingly close results to the expected values, providing strong evidence of the gravitational background radiation, and thus insight into potentially millions of SMBH binaries in the early universe.

Conclusion

Pulsars truly are a wonderful phenomenon of nature, and a reminder of how beautiful science and our universe can be. Although we were unable to get into its full depth, the story of their discovery is fascinating, and an insightful view into how the role of women in STEM is often overlooked. The properties of pulsars are not only fascinating, but useful to the science and our understanding of the universe. However, pulsars themselves are still clouded in some mystery, such as "Magnetars", which are Pulsar-like stars but with much larger magnetic fields, who erratically emit radio and X-ray radiation [3]. There is still active research going into pulsars, as well as new discoveries. Such as last year, when the highest energy pulse emitted by a neutron star was observed using the H.E.S.S. observatory in Namibia [29], and two new pulsars were detected in the globular cluster early last month by a group at the Max Planck institute in Bonn, Germany [30]. We live in an exciting time for scientific progress, and pulsars are one of many discoveries at its frontier.

Bibliography

1. Carroll, B. & D., O. *An Introduction to Modern Astrophysics* 2nd ed. (Cambridge University Press, 2017).
2. Ryden, P. B. *Quasars* Feb. 2003. https://www.astronomy.ohio-state.edu/ryden.1/ast162_8/notes36.html.
3. Bell Burnell, J. The past, present and future of pulsars. *Nat Astron* **1,** 831–834 (2017).
4. *This Month in Physics History: February 1968: The Discovery of Pulsars Announced* Feb. 2006. https://www.aps.org/publications/apsnews/200602/history.cfm.
5. HEWISH, A., BELL, S., PILKINGTON, J., *et al.* Observation of a Rapidly Pulsating Radio Source. *Nature* **217,** 709–713 (1968).
6. GOLD, T. Rotating Neutron Stars and the Nature of Pulsars. *Nature* **221,** 25–27 (1969).
7. Thorne, K. *The Death of a Star* https://calteches.library.caltech.edu/2756/1/star.pdf (1968).
8. Kong, L.-D. *et al.* Insight-HXMT Discovery of the Highest-energy CRSF from the First Galactic Ultraluminous X-Ray Pulsar Swift J0243.6+6124. *ApJL* **933** (2022).
9. Caleb, M., Heywood, I., Rajwade, K. & others. Discovery of a radio-emitting neutron star with an ultra-long spin period of 76s. *Nat Astron* **6,** 828–836 (2022).
10. Hessels, J. W. T. *et al.* A Radio Pulsar Spinning at 716 Hz. *Science* **311,** 1901–1904. eprint: https://www.science.org/doi/pdf/10.1126/science.1123430. https://www.science.org/doi/abs/10.1126/science.1123430 (2006).
11. Hobbs, M. *An Introduction to Pulsars* https://www.atnf.csiro.au/outreach/education/everyone/pulsars/index.html.
12. Becker, W. & Trümper, J. Detection of pulsed X-rays from the binary millisecond pulsar J0437 − 4715. *Nature* **365,** 528–530 (1993).
13. *Pulsar Astronomy* https://public.nrao.edu/radio-astronomy/pulsars/.
14. *About Us* https://www.skao.int/en/about-us/skao.
15. Stappers, B. *Special Topics Lecture - Pulsars: An Introduction* Oct. 2023.
16. *The Square Kilometer Array (SKA)* https://www.jodrellbank.manchester.ac.uk/research/groups/square-kilometre-array/.
17. Cooper, K. SKA Observatory (SKAO): A guide to the soon-to-be largest radio telescopes in the world. *SPACE.com.* https://www.space.com/square-kilometre-array-observatory-skao (Feb. 2023).
18. Lazio, T. J. The Square Kilometre Array Pulsar Timing Array. *Classical and Quantum Gravity* **30,** 224011 (2013).
19. Kramer, M. *et al.* Strong-Field Gravity Tests with the Double Pulsar. *Physical Review X* **11** (Dec. 2021).
20. *General Relativity survives gruelling pulsar test - Einstein at least 99.95% right!* Dec. 2006. https://www.jb.man.ac.uk/news/2006/einstein/.
21. Shao, L. General Relativity Withstands Double Pulsar's Scrutiny. *Physics* **14,** 173 (Dec. 2021).
22. Jefimenko, O. D. *A Gravitational and Electromagnetic Analogy by Oliver Heaviside.* https://sergf.ru/Heavisid.htm.
23. Maiorano, M., De Paolis, F. & Nucita, A. A. Principles of Gravitational-Wave Detection with Pulsar Timing Arrays. *Symmetry* **13,** 2418. ISSN: 2073-8994. http://dx.doi.org/10.3390/sym13122418 (Dec. 2021).
24. Thorne, K. S. *Gravitational Waves* 1995. arXiv: gr-qc/9506086 [gr-qc].
25. *International Pulsar Timing Array* https://ipta4gw.org/.
26. *Scientists use Exotic Stars to Tune into Hum from Cosmic Symphony* June 2023. https://nanograv.org/news/15yrRelease.
27. Jenet, F. A. & Romano, J. D. Understanding the gravitational-wave Hellings and Downs curve for pulsar timing arrays in terms of sound and electromagnetic waves. *American Journal of Physics* **83,** 635–645. ISSN: 0002-9505. eprint: https://pubs.aip.org/aapt/ajp/article-pdf/83/7/635/13081100/635_1_online.pdf. https://doi.org/10.1119/1.4916358 (July 2015).
28. Agazie, G. *et al.* The NANOGrav 15 yr Data Set: Evidence for a Gravitational-wave Background. *The Astrophysical Journal Letters* **951** (2023).
29. Collaboration, T. H. & others.. Discovery of a radiation component from the Vela pulsar reaching 20 teraelectronvolts. *Nat Astron* **7,** 1341–1350 (2023).
30. Abbate, F. *et al.* *A MeerKAT view of the pulsars in the globular cluster NGC 6522* 2023. arXiv: 2310.03800 [astro-ph.HE].

Image Credits

Cover Page: NASA, ESA, NRAO/AUI/NSF and G. Dubner (University of Buenos Aires), https://science.nasa.gov/missions/hubble/new-view-of-the-crab-nebula/
Background, Page 1: Casey Reed (Penn State), https://www.astronomy.com/science/earths-neutron-star-neighbor/
Background, Page 2 and 3: The Rosette Nebula, Hubble
Background, Page 4 and 5: https://www.istockphoto.com/photo/reflection-nebula-around-the-pulsar-gm1481336819-508665342
Background, Page 6 and 7: Aurore Simonnet (LIGO/Caltech/MIT/Sonoma State) https://tinyurl.com/4up7v95e
Background, Page 8: NASA, ESA and J. Olmsted (STScI), https://tinyurl.com/2p9n53ns