AstroTalk: Behind the news headlines of March–June 2021

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Cataclysmic mergers in galaxies far, far away

Recently, scientists from the Australian National University (ANU) said that they had detected a black hole swallowing a neutron star for the first time.

Neutron stars and black holes are the super-dense remains of dead stars.

On Wednesday 14 August 2019, gravitational-wave discovery machines in the USA and Italy detected ripples in space and time from a cataclysmic event dubbed GW190814, which happened about 8,550 million trillion kilometres from Earth.

ANU's professor Susan Scott said the achievement completed her team's trifecta of observations on their original wish list, which included the merger of two black holes and the collision of two neutron stars.

> "*About 900 million years ago, this black hole ate a very dense star, known as a neutron star, like Pac-man—possibly snuffing out the star instantly*," she said. "*The ANU SkyMapper Telescope responded to the detection alert and scanned the entire likely region of space where the event occurred, but we've not found any visual confirmation*."

Scientists are still analysing the data to confirm the exact nature of the two objects, but initial findings indicate the very strong likelihood of a black hole enveloping a neutron star.

> "*Scientists have never detected a black hole smaller than five solar masses or a neutron star larger than about 2.5 times the mass of our Sun*," professor Scott said. "*Based on this experience, we're very confident that we've just detected a black hole gobbling up a neutron star. However, there is the slight but intriguing possibility that the swallowed object was a very light black hole—much lighter than any other black hole we know about in the Universe. That would be a truly awesome consolation prize*."

These results are potentially far-reaching. Their impact could be felt well outside the immediate research field of gravitational-wave physicists, since the regime probed here is directly relevant to Einstein's theory of General Relativity.

General Relativity, Einstein's theory of gravity, is best tested at its most extreme, that is, close to the so-called event horizon of a black hole, the greatest distance from the black hole from where light can no longer escape. This regime is only accessible through observations of shadows of supermassive black holes and gravitational waves.

For the first time, scientists from the Australian ARC Centre of Excellence for Gravitational Wave Discovery (OzGrav), the Event Horizon Telescope (*EHT*) and the international *LIGO* Scientific Collaboration, have now outlined a consistent approach to exploring deviations from Einstein's general theory of relativity in these two different observations. This research has now confirmed—once again—that Einstein's theory accurately describes current observations of black holes, from the smallest to the largest.

Indeed, one of the hallmark predictions from general relativity is the existence of black holes. The theory provides a specific description of a black hole's effect on the fabric of space-time: a four-dimensional mesh of space (in three dimensions) and time (the fourth dimension), which encodes how objects move through space and time.

Known as the *Kerr metric*, this prediction can be related to the bending of light by gravity around a black hole, or the orbital motion of binary black holes around each other. In the recent OzGrav study, the deviations from the Kerr metric were linked to features in these black hole observations.

In 2019, the Event Horizon Telescope generated silhouette images of the black hole at the centre of the elliptical galaxy Messier 87. The black hole was found to have a mass of several billion times that of our Sun. The angular size of the shadow (that is, the extent as seen in the sky) is related to the mass of the black hole, its distance from Earth and possible deviations from General Relativity's predictions. These deviations can be calculated from the scientific data, including previous measurements of the black hole's mass and distance.

Meanwhile, since 2015 the US *LIGO* and Italian *Virgo* gravitational-wave observatories have been detecting gravitational waves from merging stellar-mass black holes. By measuring the gravitational waves from the colliding black holes, scientists can explore the mysterious nature and metrics of the black holes. The recent study focussed on deviations from General Relativity that appear as slight changes to the pitch (known as the 'chirp') and intensity of the gravitational waves, before the two black holes collide and merge.

Combining the measurements of the shadow of the supermassive black hole in Messier 87 and gravitational waves from some other binary black hole detections, GW170608 and GW190924, the researchers found no evidence for deviations from General Relativity. Ethan Payne of the Australian National University explained that the two measurements provided similar, consistent constraints.

> "*Different sizes of black holes may help break the complementary behaviour seen here between* EHT *and* LIGO/Virgo *observations*," said Payne. "*This study lays the groundwork for future measurements of deviations from the Kerr metric*."

Returning now to this month's lead story about black hole–neutron star mergers, in January 2020 two additional gravitational-wave measurements were made of black holes that gobbled up their neutron star companions. The cataclysmic events that were observed occurred a long time ago, in two galaxies located about 900 million to a billion light-years away.

Discovered by an international team of astrophysicists, the two events were detected just 10 days apart. The findings will enable scientists to draw some of the first conclusions about the origins of these rare binary systems and how often they merge.

> "*Gravitational waves have allowed us to detect collisions of pairs of black holes and pairs of neutron stars, but the mixed collision of a black hole with a neutron star has been the elusive missing piece of the family picture of compact object mergers*," said Chase Kimball, a PhD student at Northwestern University (USA), who co-authored the study. "*Completing this picture is crucial to constraining the host of astrophysical models of compact object formation and binary evolution. Inherent to these models are their predictions of the rates that black holes and neutron stars merge amongst themselves. With these detections, we finally have measurements of the merger rates across all three categories of compact binary mergers*."

The team observed the two new gravitational-wave events—GW200105 and GW200115—on 5 and 15 January 2020 during the second half of the *LIGO* and *Virgo* detectors' third observing run. Although multiple observatories carried out several follow-up observations, none observed light from either event, consistent with the measured masses and distances.

> "*Following the tantalising discovery, announced in June 2020, of a black-hole merger with a mystery object, which may be the most massive neutron star known, it is exciting also to have the detection of clearly identified mixed mergers, as predicted by our theoretical models for decades now*," said Vicky Kalogera, professor at Northwestern University. "*Quantitatively matching the rate constraints and properties for all three population types will be a powerful way to answer the foundational questions of [their] origins*."

All three large gravitational-wave detectors (both *LIGO* instruments located at opposite ends of the USA and the *Virgo* instrument) detected GW200115, which resulted from the merger of a 6 solar-mass black hole with a 1.5 solar-mass neutron star. With observations of the three widely separated detectors on Earth, the direction to the gravitational waves' origin can be determined to a section of the sky equivalent to the area covered by 2900 full moons.

Just 10 days earlier, *LIGO* detected a strong signal from GW200105, using just one detector while the other was temporarily offline. Although *Virgo* was also observing, the signal was too faint for *Virgo* to detect it. Nevertheless, the gravitational waves enabled the astronomers to infer that the signal was caused by a 9 solar-mass black hole colliding with a 1.9 solar-mass compact object, which they ultimately concluded was a neutron star.

Because the signal was strong in only one detector, the astronomers could not precisely determine the direction of the gravitational waves' origin. Although the signal was too faint for *Virgo* to confirm its detection, its data did help narrow down the source's potential location to about 17% of the entire sky, which is an enormous area equivalent to 34,000 full moons.

Because the two events are among the first confident observations of gravitational waves from black holes merging with neutron stars, the researchers now can estimate how often such events happen throughout the universe. Although not all events are detectable, the researchers expect that roughly one such merger per month happens within a distance of one billion light-years.

While it is unclear where these binary systems form, astronomers identified three likely cosmic origins: stellar binary systems, dense stellar environments including young star clusters, and the centres of galaxies.

> "*We've now seen [some of] the first examples of black holes merging with neutron stars, so we know that they're out there*," postdoctoral researcher Maya Fishbach (Northwestern University) said. "*But there's still so much we don't know about neutron stars and black holes—how small or big they can get, how fast they can spin, how they pair off into merger partners. With future gravitational wave data, we will have the statistics to answer these questions, and ultimately learn how the most extreme objects in our universe are made*."

The Northwestern team may be in luck. OzGrav scientists may have provided just that information! They have described a way to determine the birth population of double neutron stars. Their recently published study observed different life stages of these neutron star systems.

By studying neutron star populations using gravitational-wave measurements, scientists can learn more about how they formed and evolved. So far, there have been only two double neutron star systems detected by gravitational-wave detectors; however, many of them have been observed using radio astronomy.

One of the double neutron stars observed in gravitational-wave signals, GW190425, is far more massive than the ones in typical galactic populations observed in radio astronomy, with a combined mass of 3.4 times that of our Sun. This raises the question: why is there a lack of these massive double neutron stars in radio astronomy? To find an answer, OzGrav PhD student Shanika Galaudage, from Monash University in Melbourne (Australia), investigated how to combine radio and gravitational-wave observations.

Radio and gravitational-wave astronomy enables scientists to study double neutron stars at different stages of their evolution. Radio observations probe the lives of double neutron stars, while gravitational waves study their final moments of life. To achieve a better understanding of these systems, from formation to merger, scientists need to study the connection between radio and gravitational-wave populations: their birth populations.

Shanika and her team determined the birth mass distribution of double neutron stars using radio and gravitational-wave observations.

> "*Both populations evolve from the birth populations of these systems, so if we look back in time when considering the radio and gravitational-wave populations we see today, we should be able to extract the birth distribution*."

The key is to understand the delay-time distribution of double neutron stars: the time between the formation and merger of these systems. The researchers hypothesised that more massive double neutron star systems may be fast-merging systems, in the sense that they're merging too fast to be visible in radio observations and could only be seen in gravitational waves.

The study found mild support for a fast-merging channel, indicating that massive double neutron star systems may not need a fast-merging scenario to explain the lack of observations in radio populations.

> "*We find that GW190425 is not an outlier when compared to the broader population of double neutron stars*," said co-author Christian Adamcewicz, also from Monash University. "*So, these systems may be rare, but they're not necessarily indicative of a separate fast-merging population*."

In future gravitational-wave detections, researchers can expect to observe more double neutron star mergers.

> "*If future detections reveal a stronger discrepancy between the radio and gravitational-wave populations, our model provides a natural explanation for why such massive double neutron stars are not common in radio populations*," added co-author Simon Stevenson, an OzGrav postdoctoral researcher at Swinburne University of Technology, also in Melbourne.

Figure 1: Artist's depiction of a black hole about to swallow a neutron star. (Credit: Carl Knox, OzGrav/Swinburne University)

Figure 2: An artistic image inspired by a black hole–neutron star merger event. (Credit: Carl Knox, OzGrav/Swinburne University)

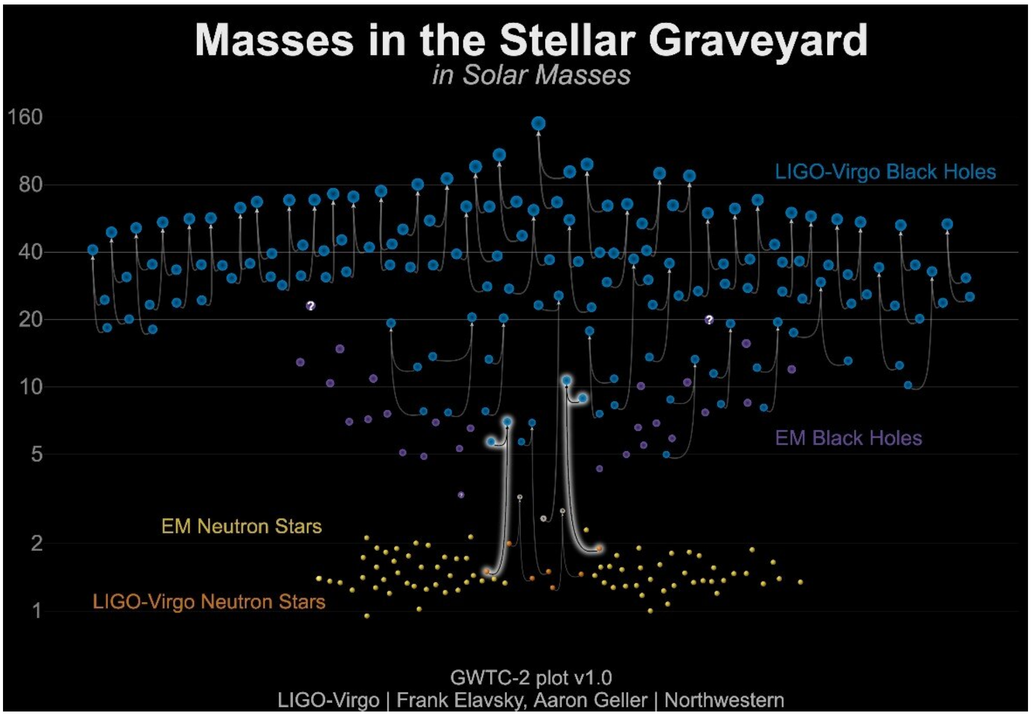

Figure 3: The masses of neutron stars and black holes measured through gravitational waves (blue and orange) and electromagnetic observations (yellow and purple). GW 200105 and GW 200115 are highlighted as the merger of neutron stars with black holes. (Credit: © LIGO-Virgo/Frank Elavsky, Aaron Geller/Northwestern University)

Figure 4: Artist's impression of binary black holes about to collide. (Credit: Mark Myers, OzGrav/Swinburne University)

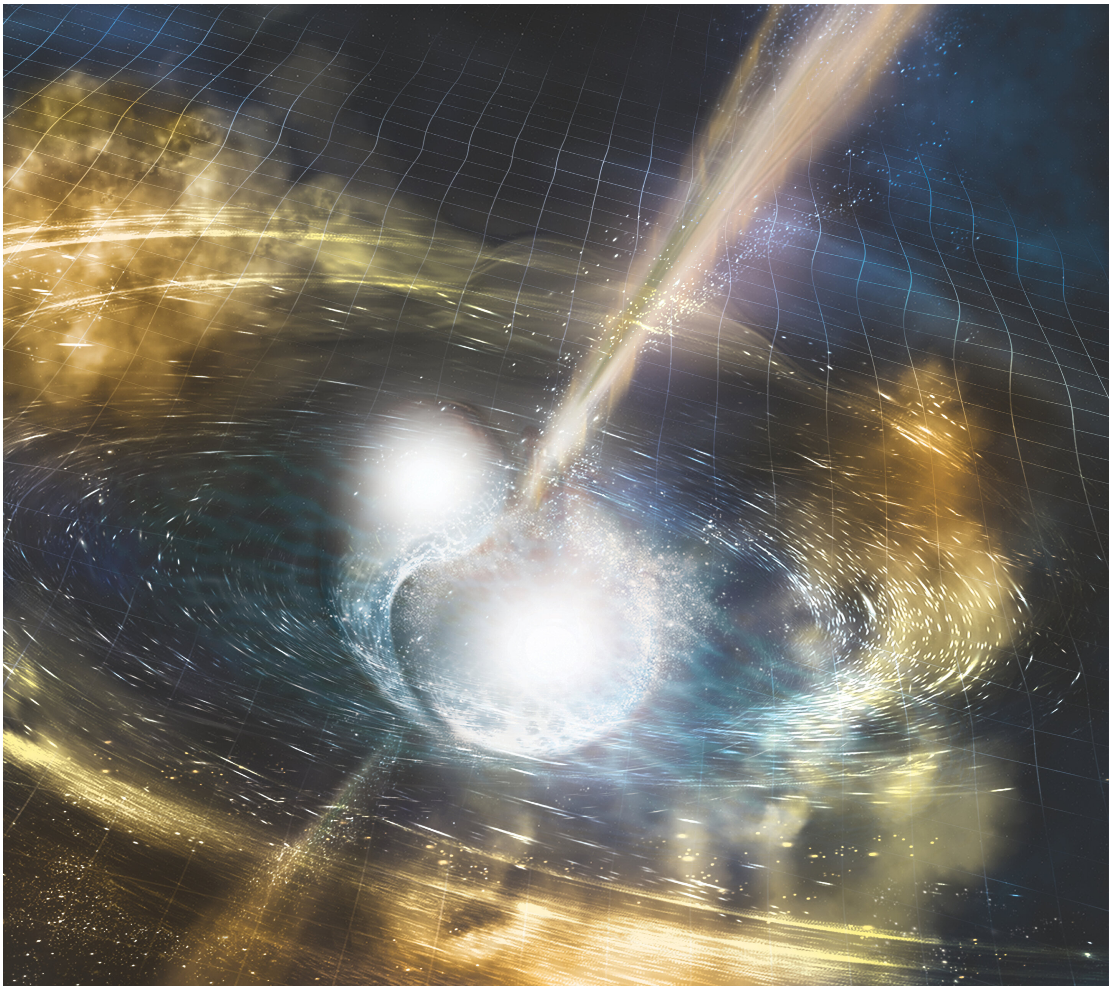

Figure 5: Artist's illustration of a double neutron star merger. (Credit: LIGO, Sonoma State University, A. Simonnet)

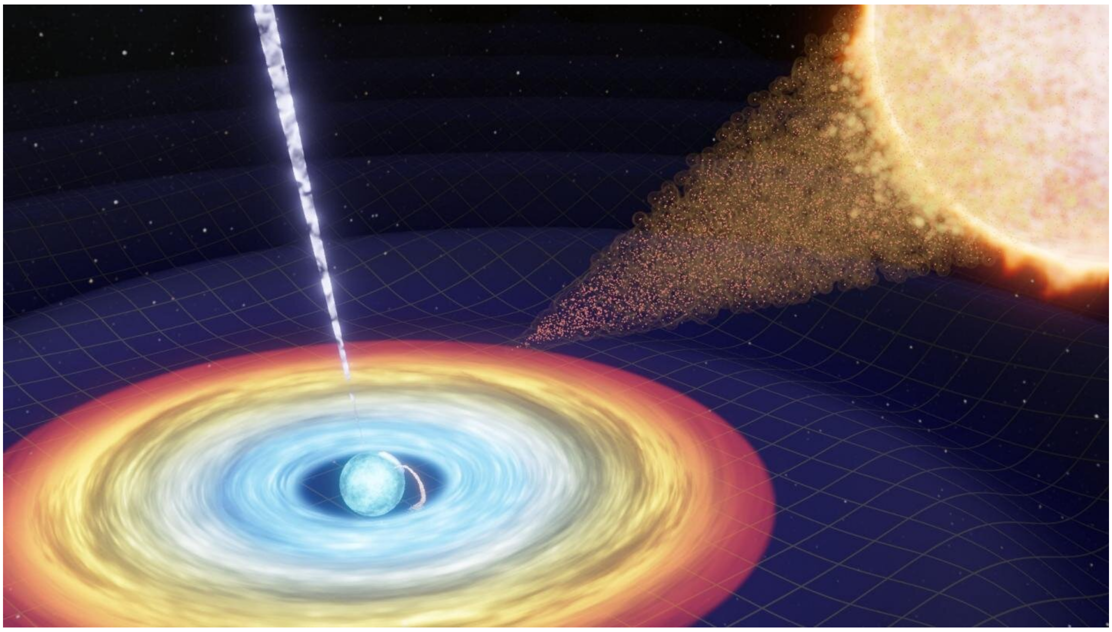

Figure 6: Image of continuous gravitational waves. (Credit: Mark Myers, OzGrav/Swinburne University)