SEARCH FOR CONTINUOUS GRAVITATIONAL WAVES FROM YOUNG SUPERNOVA REMNANTS IN EARLY O3 DATA

Core-collapse supernovae are the violent, explosive deaths of massive stars. The remnant of the explosion is an ultra-dense neutron star surrounded by debris from the explosion (Fig. 1). The debris from the explosion can stretch across light-years, but the neutron star in the centre is approximately 30 km (12 miles) across and has a mass about 1.4 times the mass of the Sun. Neutron stars are some of the densest objects in the universe. The composition and underlying physics of neutron stars remains one of the most tantalizing mysteries in physics, inspiring interest across a range of fields, covering astrophysics, nuclear physics, particle physics, and condensed matter physics. For the Advanced LIGO and Advanced Virgo detectors, neutron stars are important because they are likely sources of continuous gravitational waves (CWs). In a recent paper, we search for continuous gravitational waves from fifteen young supernova remnants in our galaxy using six months of data from 2019, which constitutes the first half of the third observing run of the advanced detectors, called O3a for short.

While transient bursts of gravitational waves are now regularly observed, continuous gravitational waves continue to evade detection. This is because transient bursts are loud and short, while continuous gravitational waves are very quiet and hard to differentiate from noise. To detect CWs, we have to be patient, gathering data over a long period of time and searching for tiny but persistent fluctuations that match our signal model. For a typical search for CWs, we're searching for waves generated by a rapidly rotating neutron star. Any deviation from a perfectly uniform star will produce gravitational waves at twice the rotation frequency of the star, with larger deviations producing a larger gravitational-wave strain (i.e. a louder signal). We call such a star "triaxial" because it's a three dimensional ellipse, similar to a rugby ball.

There are many supernova remnants within our galaxy. We choose fifteen young supernova remnants between 100 and 10 000 years old, but for which the rotation frequency is unknown. We target young supernova remnants because young neutron stars are more likely to have non-uniform deformations than older stars. Young neutron stars also rotate faster, producing a larger gravitational wave strain. But because we do not know how fast the neutron star is rotating, we have to search a wide range of frequencies. Young neutron stars also lose rotational energy and slow down over time (spin down), so we also need to search over possible spin-down rates. Lastly, observations of isolated neutron stars with frequency measurements suggest there may be small, random fluctuations in the rotation frequency.

In a normal search (called a coherent search), we construct templates of what the signal should look like over the observation time and try to match those signals to the data. If we test the right signal template and if the number of templates isn't too high, then a coherent search is very sensitive. But we have fifteen targets without a frequency estimate that could change their rotation frequency or undergo small, random frequency changes. In this scenario, a coherent search is too computationally intensive. We instead use three semi-coherent methods to search the early O3 data efficiently. A semi-coherent search applies a coherent search to small blocks of data and joins them together to cover the full observation time.

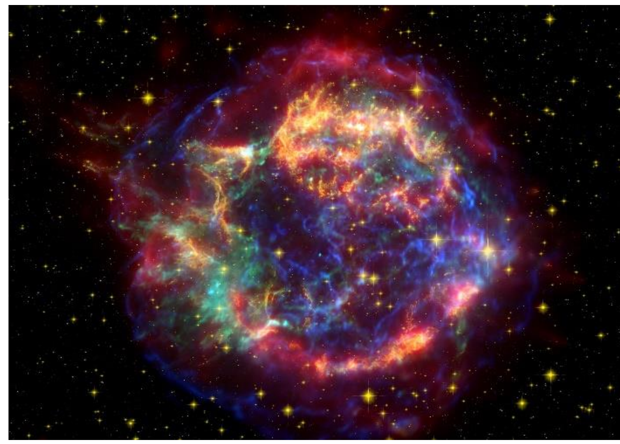

Figure 1: *Cassiopeia A, one of the young supernova remnants targeted in this search. Image credit: NASA/JPL-Caltech/Krause et al.*

FIGURES FROM THE PUBLICATION

For more information on these figures and how they were produced, read the freely available preprint.

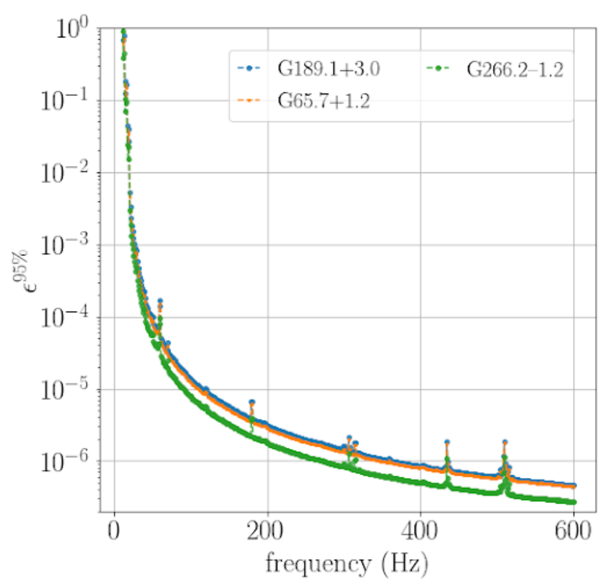

Figure 2: *The 95% upper limits on neutron star ellipticity ε for a few of the analyses and targets in the paper. The horizontal axis is the frequency at which we would detect a gravitational wave signal; the vertical axis is the 95% upper limit on the ellipticity. The green (G266.2-1.2), blue (G189.1+3.0), and orange (G65.7+1.2) curves show the minimum possible ellipticity we could detect. This is an upper limit on how elliptic the neutron star could be (because if it was more elliptical than this, we would have detected it!).*

Smaller blocks of data need less templates to search, so a semi-coherent search is much more computationally efficient. We apply three semi-coherent algorithms to early O3 data: one optimised for sensitivity, one optimised for a rapidly changing signal, and one optimised for a particular astrophysical model. None of the three searches report any CW signal.

No detection, however, doesn't mean there are no results. We can estimate the [sensitivity]() of our search and from that infer properties about the stars we searched. A rapidly rotating neutron star emits CWs, and the more deformed a star is, the louder the signal should be. By placing a limit on the signal strength, we can put an upper limit on how deformed the target neutron star could be. The asymmetry of a neutron star is measured in the parameter ε, which stands for ellipticity. Different models for neutron stars predict different limits on the ellipticity, but most predict $\varepsilon < 10^{-6}$. We show the ellipticity limits for three targets in Figure 2. The vertical axis is the 95% upper limit on ε obtained in this search. The horizontal axis is the gravitational wave frequency, which affects the ellipticity in two ways. Firstly, the gravitational wave strain at a given frequency is louder for a more elliptical star. Secondly, LIGO and Virgo's sensitivity is frequency-dependent, so our limits on the gravitational wave strain vary across the full frequency range. We manage to constrain the ellipticity below the theoretical maximum ($\varepsilon < 10^{-6}$). As this limit improves, we will be able to rule out physical models trying to predict neutron star properties.

Triaxial neutron stars aren't the only way a neutron star could generate CWs. Stellar rotation can also drive CWs through r-mode oscillations within the neutron star, with the scale of the oscillations parameterized by the amplitude α. The theoretical upper limit on the scale of the oscillations is $\alpha < 10^{-3}$. A limit on the strain from an elliptic neutron star can be converted into a limit on α, as we do in Figure 3. The vertical axis is our 95% confidence limit on α and the horizontal axis is the gravitational wave frequency (in Hz). We find $\alpha < 10^{-3}$ above 150 Hz for three targets, restricting how large the r-mode amplitudes could be in these stars.

As data collection continues and our methods improve, the probability of making the first detection increases. Until then, we constrain physical models based on non-detection and push to increase the sensitivity of our searches.

Read a free preprint of the full scientific article here.

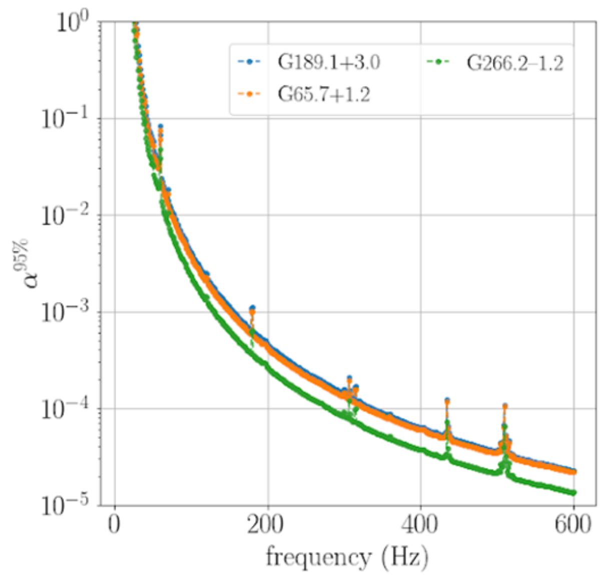

***Figure 3:** The 95% upper limits on r-mode oscillation amplitude α for a few of the analyses and targets in the paper. The horizontal axis is the frequency at which we would detect a gravitational wave signal; the vertical axis is the 95% upper limit on the amplitude. The green (G266.2-1.2), blue (G189.1+3.0), and orange (G65.7+1.2) curves show the minimum possible amplitude we could detect. This is an upper limit on how strong r-modes in the neutron star could be (because if they were stronger than this, we would have observed them!).*

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www.ligo.org

www.virgo-gw.eu

gwcenter.icrr.u-tokyo.ac.jp/en/

GLOSSARY

Continuous gravitational wave: Long-lasting form of gravitational radiation. See here for more details.

Ellipticity: Measure of how far from spherical a body is, defined as the relative deformation across the equatorial plane with respect to the deformation along the perpendicular direction.

Light-year: A unit of distance equivalent to the distance that light travels in one year. A light year is approximately equal to 9.46 trillion kilometers (or roughly 5.88 trillion miles).

LIGO: The Laser Interferometric Gravitational-Wave Observatory (LIGO) is a US-based pair of gravitational-wave detectors. One is situated near Livingston, Louisiana, and the other near Hanford, Washington. Both detectors are large-scale laser interferometers, with two perpendicular 4 km long arms, that attempt to measure any changes in the relative arm length caused by a passing gravitational wave.

Massive star: Massive stars have masses more than 8 times the mass of the Sun. Only stars that massive can form a neutron star after they explode as a supernova. If they have lower masses, the remnant becomes a white dwarf star

Neutron star: Extremely dense object which remains after the collapse of a massive star. A typical neutron star has a mass half a million times that of the Earth but is only about 30 km across.

R-modes: Waves in the liquid which makes up most of a neutron star. They have a frequency which is comparable to the spin frequency of the star, so for young neutron stars they could be in the LIGO and Virgo frequency band.

Sensitivity: A description of a detector's ability to detect a signal. Detectors with lower noise are able to detect weaker signals and therefore are said to have higher (or greater) sensitivity.

Strain: fractional change in the separation of two measurement points due to the deformation of space-time caused by a passing gravitational wave. The typical strain of even the strongest gravitational waves reaching Earth is very small — typically less than 10^{-21}.

Supernova: A violent explosion, often spotted a rapidly appearing bright object in the sky, which then fades away. A supernova may outshine the rest of its galaxy. There are a variety of different supernovae. Some come from the collapse of massive stars, others may come from the collision of two white dwarfs.

Transient gravitational waves: gravitational waves resulting from a short, often cataclysmic event, e.g. binary compact mergers. Most transient gravitational waves appear in the detector only for seconds or less.

Upper limit: The upper limit on some quantity (e.g. gravitational wave strain) is the smallest value we would detect with 95% confidence. So if we have not detected anything, we are 95% certain that no sources producing higher values are out there.

Virgo: The Virgo detector is a ground-based interferometer located in Cascina, Italy, near Pisa.