A SENSITIVE SEARCH FOR CONTINUOUS GRAVITATIONAL WAVES FROM SCORPIUS X-1 IN O3

SUMMARY

This is the latest and most sensitive search for continuous gravitational waves (CWs) from the low-mass X-ray binary Scorpius X-1, a neutron star in a binary orbit with a low-mass star. We used Advanced LIGO data from the third LIGO-Virgo-KAGRA (LVK) observing run to look for signals across a wide range of possible frequencies. We did not detect gravitatonal waves from Scorpius X-1, but set limits which are beginning to constrain possible models. In particular, we have reached one stringent benchmark at some signal frequencies.

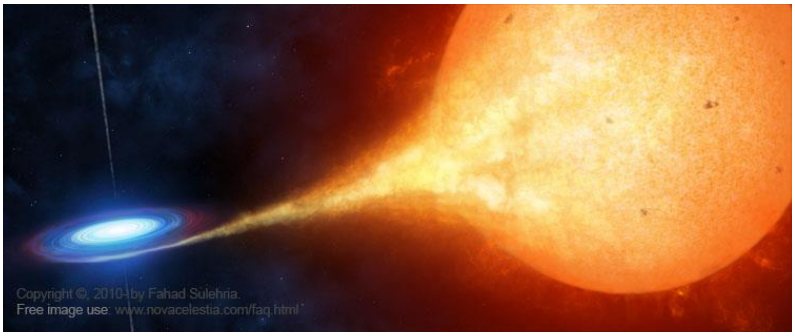

Figure 1: An artist's impression of a low-mass X-ray binary like Scorpius X-1. (Astronomical Illustrations and Space Art, by Fahad Sulehria, NovaCelestia)

WHAT ARE WE LOOKING FOR?

Since their first observing run in 2015, the LIGO and Virgo detectors have detected many gravitational wave signals from the inspiral and merger of binaries of compact objects such as black holes or neutron stars. These compact binary coalescences (CBCs) emit relatively strong transient signals that are observable in detectors for only a few seconds. However, general relativity also predicts that other astrophysical systems emit gravitational waves continuously, weaker than the signals from CBCs, but over long periods of time. Therefore, searches for CWs can combine data over long stretches (such as an entire observing run) to accumulate signal and increase the chance of detection.

Dense neutron stars (NSs) spinning at incredible rates of up to hundreds of rotations a second are the most likely sources of CWs. Any slight asymmetry in the distribution of the mass of the NS will generate gravitational waves (GWs) at a frequency which is twice the rotation frequency of the NS. When these waves reach our detectors on Earth, the frequency will be Doppler shifted due to the motion of the detectors as the Earth rotates and moves through its orbit, as well as any time-varying motion of the NS. Thus the properties of the system, such as sky position and orbital velocity, determine the precise form of the signal.

The most promising known source of CWs is the Low-mass X-ray binary (LMXB), Scorpius X-1 (Sco X-1). An LMXB (Figure 1) is a system consisting of a compact object in a binary orbit with a lower mass companion star. Sco X-1 is an LMXB in our galaxy which is the brightest persistent X-ray source (other than the Sun), and is relatively close by at only 9000 light years away. In an LMXB, the NS pulls gaseous matter from the companion star in a process known as accretion. The accreted material creates a ``bump'' on the surface of the NS, causing an asymmetry in the mass distribution which generates CWs as the NS rotates.

Accretion of matter onto the NS also influences its rotation. Accretion can ``spin up'' the NS, increasing its rotation speed, while GWs, along with other forces such as the interaction of the NS's magnetic field with its environment, can ``spin it down''. When the spinup and spindown torques cancel each other, the NS spin remains constant. The scenario in which this spin equilibrium is maintained by accretion and GW alone is known as ``torque balance'', and gives an optimistic (because it neglects other contributions to the spindown) estimate of the expected GW signal strength The accretion also produces X-rays which can be observed with X-ray telescopes to estimate the accretion rate. Observations of Sco X-1 over a wide range of electromagnetic frequencies from radio to X-rays have given information about the sky position, and parameters of the neutron star's orbit. This information is essential in determining the possible GW signals, making our search an example of multi-messenger astronomy.

To date, many searches have been carried out using methods including radiometer, Viterbi, and the cross-correlation method used here.

HOW DID WE SEARCH?

The cross-correlation method looks for correlations between data segments taken at different times and/or in different detectors, using the waveform model of a rotating neutron star to determine the expected correlations. To construct this waveform, we need to use properties of the system such as signal frequency, sky location and orbital parameters. For Sco X-1, the frequency is unknown, while the sky position is well determined by electromagnetic observations. The orbital parameters are known somewhat imprecisely, so we need to perform the search using many possible sets of parameters (signal frequency, and the period, phase and size of the orbit). This search only considers correlations between data separated by no more than an adjustable time offset called the coherence time. Using a longer coherence time makes the search more sensitive, but greatly increases the computing cost, mostly because the parameter space points at which we perform the search must be closer together. We thus choose the coherence time to balance these considerations, using longer coherence times in regions of parameter space where the signal is more likely to be found, or where the increase in computing cost is less.

We analyzed data from the third observing run run (O3), which ran from April 2019 to March 2020; taking into consideration rejection of data from times when a detector was not taking usable data, this amounted to about 240 days' worth of data from the LIGO Hanford detector and 250 from the LIGO Livingston detector. The coherence time ranged from 240 to 18,720 seconds.

WHAT DID WE LEARN?

The result of our search is a signal-to-noise ratio (SNR) for each combination of parameter values searched. If the SNR at a point in parameter space is higher than one would expect from data containing only noise, we ``follow up'' this candidate as a possible detection. We do this by re-analyzing the data with a longer coherence time and a tight grid of parameter-space points around the candidate. If the SNR increases, we repeat the process. We also perform this analysis on candidates arising from simulated signals. Figure 2 shows that none of the candidates from the search increased their SNRs as a true signal would.

FIGURES FROM THE PUBLICATION

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

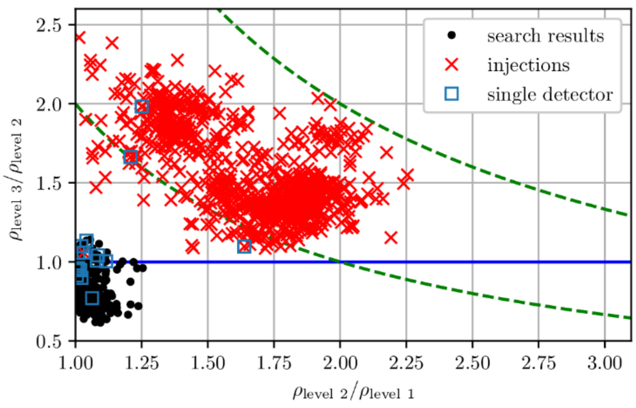

Figure 2: This figure shows the results of follow-up analyses of potential signals from the search. The x-axis shows the ratio of signal-to-noise ratios (SNRs) before and after a quadrupling of the coherence time in the cross-correlation, which should theoretically double the SNR. The y-axis shows the ratio of SNRs before and after a second quadrupling. (The green dashed lines show constant values of x times y, i.e., the ratio of SNRs before and after the two quadruplings taken together.) The red crosses show simulated injected signals, whose SNRs increase with each increase in coherence time. In comparison, the SNRs of the search candidates (black dot) do not follow the expected behavior of a true signal.

Since we do not have an apparent detection, we set upper limits on the strength of GWs from Sco X-1, as a function of frequency (Figure 3). The X-1, as a function of frequency (Figure 3). The upper limits are chosen such that, if a signal were present at that amplitude or larger, our search would have a 95 % probability of producing an SNR higher than we saw at that frequency. These results are the most sensitive constraints on the strength of Sco X-1's GW emission to date, and probe amplitudes predicted by models of the torque balance scenario.

With improved sensitivity in future Advanced LIGO-Advanced Virgo-KAGRA observing runs, we expect to be able to search for even weaker signals from Sco X-1. In a realistic situation with other spindown mechanisms in addition to GWs, the GW strength is expected to be lower than the nominal torque balance amplitude. Thus, surpassing these levels means that we have the potential to probe more realistic scenarios and to actually detect GWs from Sco X-1 in future observing runs.

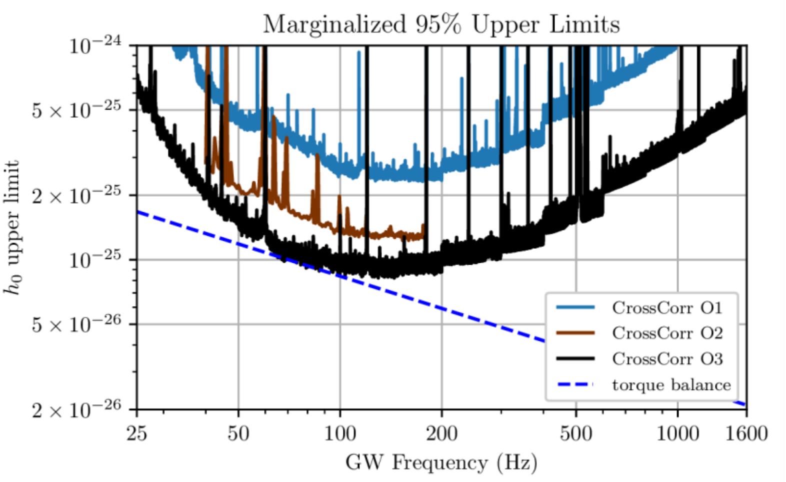

Figure 3: This figure shows the 95% upper limits set on the gravitational wave amplitude h_0 by the O3 cross-correlation search, along with the results of previous cross-correlation searches for comparison, For the first time, the sensitivity of the search has reached (at signal frequencies between 60 and 100 hertz) the predictions of the torque balance model, marginalized over the unknown inclination angle of the neutron star spin.

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The cross-correlation search for periodic gravitational waves

Updated analysis: Search for Gravitational Waves from Scorpius X-1 in LIGO O3 Data With Corrected Orbital Ephemeris

GLOSSARY

Compact object: An extremely dense astrophysical object such as a black hole, neutron star, or white dwarf.

Hertz: A unit of frequency equal to one cycle per second.

Inclination angle: Angle between the spin axis of a neutron star and a reference direction such as the line of sight.

Low-mass X-ray binary (LMXB): A binary system consisting of a compact object such as a white dwarf, a neutron star or a black hole, and a lower-mass companion star, in which the compact object is accreting matter from the companion, generating X-rays.

Marginalization: A statistical technique where we average over the possible values of a quantity that affects our observations, but which we're not trying to measure.

Multi-messenger astronomy: When the same object or system is studied with different wavelengths of photons, this is called multi-wavelength astronomy. For example, the neutron star Scorpius X-1 is observed in radio waves and X-rays, while its companion star was detected by analyzing the visible light from the system. Expanding this concept to include astrophysical messengers that aren't part of the electromagnetic spectrum, like gravitational waves, is called multi-messenger astronomy.

Neutron star: Collapsed core of a star at the end of its evolution, usually with a mass around 1.4 Solar masses, but just a few kilometers in diameter, making it an extremely dense object!

Parameter: a quantity that influences the form of a GW signal, such as signal frequency or binary orbital period.

Signal-to-noise ratio (SNR): The ratio of the signal power to the noise power. It measures the strength of the signal compared with the sources of noise that contaminate it.

Strain: The fractional change in the distance between two reference points due to the deformation of spacetime by a passing gravitational wave.

Upper limit: The maximum possible value for a quantity consistent with its non-detection in the data. In this report, the quantity of interest is the maximum intrinsic gravitational-wave strain amplitude of a given CW signal arriving at Earth. Because we did not detect any signal, we set a 95% confidence level limit, meaning that an actual signal with that strain amplitude (or above) would produce an SNR higher than what was measured in 95 % (or more) of the time.