

Searching for gravitational waves from Cassiopeia A with LIGO

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Abstract. We describe a search underway for periodic gravitational waves from the central compact object in the supernova remnant Cassiopeia A. The object is the youngest likely neutron star in the Galaxy. Its position is well known, but the object does not pulse in any electromagnetic radiation band and thus presents a challenge in searching the parameter space of frequency and frequency derivatives. We estimate that a fully coherent search can, with a reasonable amount of time on a computing cluster, achieve a sensitivity at which it is theoretically possible (though not likely) to observe a signal even with the initial LIGO noise spectrum. Cassiopeia A is only the second object after the Crab pulsar for which this is true.

1. Introduction

The LIGO Scientific Collaboration (LSC) has so far published three types of searches for periodic gravitational waves (GWs): searches for known non-accreting pulsars [1; 2; 3], for the non-pulsing low-mass X-ray binary Sco X-1 [4; 5], and all-sky searches for as yet unknown neutron stars [4; 6; 7]. The first and last types of search are approaching the indirect upper limits on

gravitational wave emission inferred from the observed spindowns (spin frequency derivatives) of pulsars and supernova-based estimates of the neutron star population of the galaxy [4].

Here we discuss the first of a fourth type of search for periodic gravitational waves: directed searches, which target likely neutron stars whose sky position is known to high accuracy, but whose spin frequencies and frequency evolution are not known at all. We describe such a search, which is currently underway, directed at the central compact object in the supernova remnant Cassiopeia A (Cas A). The data analysis challenge is to search a large parameter space of possible frequencies and frequency evolutions. We describe the object, estimate the computational costs of the search, and show that when the search of data from LIGO’s recently completed S5 run is completed, it will beat the indirect limit on GW strain for Cas A.

2. The central compact object in Cas A

Cas A is a core-collapse supernova remnant, currently the youngest known in the Galaxy [8]. A central X-ray point source was discovered in first-light images taken by the Chandra X-Ray Observatory, indicating the presence of a compact central object (CCO). The nature of the CCO remains uncertain. No radio pulsations or γ -ray emission have been observed, and there is no pulsar wind nebula observed in X-ray or radio; it is unlikely therefore that the CCO is an active pulsar [9]. Proposed explanations include that it might be a young radio-quiet neutron star, or an accretion disk associated with a neutron star or black hole, or that it might be related to a type of slowly rotating neutron star known as an anomalous X-ray pulsar (AXP) or a soft γ -ray repeater (SGR) [9; 10]. Only in the first scenario could GW emission be detectable by LIGO. What makes Cas A an attractive target is its youth: the stars with the highest indirect limits (see next section) on gravitational radiation are young, and one could argue on theoretical grounds that any deformations left over from the violent birth of the star have had less time to be smoothed away by mechanisms such as viscoelastic creep.

For the purpose of a directed search, we need to know the object’s right ascension and declination. Chandra observations [9] have obtained these to sub-arcsecond accuracy [$\alpha = 23\text{h}23\text{m}(27.945 \pm 0.05)\text{s}$, $\delta = 58^\circ 48'(42.51 \pm 0.4)''$], which is sufficient for any GW observation. In order to define the range of search parameters and give an indirect limit on GW emission from the object, we also need the distance, age, and moment of inertia. The distance to Cas A has been estimated from the radial velocities of knots of ejected material to be $3.4_{-0.1}^{+0.3}$ kpc [11]. Extrapolation of the proper motions of outer ejecta knots suggest a convergence date of 1681 ± 19 , consistent with a possible observation by John Flamsteed in 1680 [8]. Since computational costs are higher for younger objects, we play it safe by taking 300 years (the approximate lower bound) as our fiducial age estimate. In what follows we use the canonical neutron star moment of inertia of 10^{45} g cm², although modern equations of state predict values higher for most neutron stars by a factor 2 or 3 [12].

3. Indirect limits

Indirect limits on the gravitational wave emission from rotating neutron stars are found by assuming that the gravitational wave luminosity is bounded by the time derivative of the total rotational kinetic energy:

$$\left(\frac{dE}{dt}\right)_{\text{gw}} = \frac{32G}{5c^5} I_{zz}^2 \epsilon^2 (\pi f)^6 \leq -\frac{d}{dt} \left(\frac{1}{2} \pi^2 I_{zz} f^2\right) = -\left(\frac{dE}{dt}\right)_{\text{rot}}, \quad (1)$$

where ϵ is the equatorial ellipticity, I_{zz} the principal moment of inertia (assumed constant), and f the gravitational wave frequency (assumed to be twice the spin frequency) [4; 13]. This condition is rearranged to give the “spindown” upper bounds on the ellipticity and the GW

strain tensor amplitude h_0 :

$$\epsilon \leq \sqrt{\frac{5c^5}{32\pi^4 G I_{zz}} \frac{-\dot{f}}{f^5}}, \quad h_0 \leq \frac{1}{d} \sqrt{\frac{5G I_{zz}}{2c^3} \frac{-\dot{f}}{f}}. \quad (2)$$

The second limit is found from the first by substituting

$$h_0 = \frac{4\pi^2 G I_{zz} \epsilon f^2}{c^4 d}. \quad (3)$$

where d is the distance of the source [4; 14].

For Cas A, the GW frequency f and its time derivative \dot{f} are unknown, but the age is known. If we assume that the star is spinning down with $\dot{f} \propto f^n$, and that it is currently spinning significantly more slowly than it was at birth, we can relate the frequency evolution to the characteristic age τ and braking index n by [4; 15; 16]

$$\tau \approx \frac{1}{n-1} \frac{f}{-\dot{f}}, \quad n = \frac{f\ddot{f}}{\dot{f}^2}. \quad (4)$$

If the spindown is GW-dominated, $n = 5$ and τ is the true age of the star. Substituting into the spindown limits (2) gives

$$\epsilon_{\text{age}} \leq \sqrt{\frac{5c^5}{128\pi^4 G I_{zz} \tau f^4}}, \quad h_{\text{age}} \leq \frac{1}{d} \sqrt{\frac{5G I_{zz}}{8c^3 \tau}}. \quad (5)$$

Using the numbers for Cas A from the previous section we get

$$h_{\text{age}} \leq 1.2 \times 10^{-24} \left(\frac{3.4 \text{ kpc}}{d} \right) \sqrt{\left(\frac{I}{10^{45} \text{ g cm}^2} \right) \left(\frac{300 \text{ yr}}{\tau} \right)} \quad (6)$$

$$\epsilon_{\text{age}} \leq 3.9 \times 10^{-4} \left(\frac{100 \text{ Hz}}{f} \right)^2 \sqrt{\left(\frac{10^{45} \text{ g cm}^2}{I} \right) \left(\frac{300 \text{ yr}}{\tau} \right)}. \quad (7)$$

Some theories of quark matter allow for ellipticities this high, though normal neutron star models do not [17; 18; 19]. An internal magnetic field of order 10^{16} G could also produce such ellipticities [20; 21; 22; 23], although it is not clear if such a field is stable, and if the external field is this strong then the star by now has spun down out of the LIGO frequency band. The age-based indirect limits serve, like the spindown limits, as indicators of which objects are interesting, but since they are based on less information they are not as solid as the spindown limits. It is not known if Cas A spins in the LIGO band (period ≤ 50 ms), and indeed only 10% of known pulsars do so [24]. Thus a search such as we describe could detect an object on the speculative end of the range of theoretical predictions.

4. Search method

The LSC uses both fully coherent [1; 4] and semi-coherent [5; 6; 7; 25] methods to search for periodic gravitational waves. Semi-coherent methods are computationally cheaper than coherent methods, but coherent methods can achieve greater sensitivity if the cost is feasible.

For Cas A the integration time needed is short enough (see next section) for us to pursue enhanced sensitivity without undue computational cost. We therefore use the fully coherent \mathcal{F} -statistic search [4], as implemented by the `ComputeFStatistic_v2` routine in the LSC Algorithm

Library [26]. This routine computes optimal filters for the gravitational wave signal, including modulation by the detector beam patterns, in multiple interferometers which are treated as a coherent network [14; 27]. This search uses data from the 4km LIGO interferometers at Hanford, WA, and Livingston, LA.

The computation is conducted in the frequency domain using short Fourier transforms (SFTs) of segments of strain data, typically of 30 minutes duration so that the GW frequency will remain in one frequency bin over the length of the SFT [4]. The SFTs are vetoed by a suite of data quality flags to remove poorer quality data. For windows of up to 15 days during the first year of the S5 run the duty cycle, or ratio of post-veto SFT live time to total time span (averaged over interferometers) can somewhat exceed 70%.

A special requirement of a search for Cas A is that, due to its young age and therefore the increased size of the spindown parameter space, the search will require a second frequency derivative (see next section), giving a three-dimensional search in frequency, and first and second spindown derivatives. This has required the extension of existing LSC software to efficiently cover a three-dimensional space using the parameter space metric. The points are distributed on a body-centered cubic (bcc or A_3^*) lattice, which is known to be the optimal lattice covering in three dimensions [28].

In the event no plausible signal is found, we will set upper limits by methods similar to the frequentist analyses in [1; 4]. These are based on Monte Carlo simulations searching the data for a multitude of software-injected signals with a distribution of amplitudes, inclination angles, and polarization angles in each frequency bin. We will also test on a smaller set of simulated signals which were hardware injected into the S5 data.

5. Estimated cost and sensitivity

The sensitivity of a search for periodic signals can be put in terms of the 95% confidence limit on GW strain tensor amplitude, which takes the form

$$h_0^{95\%} = \Theta \sqrt{S_h(f)/T_{\text{dat}}}. \quad (8)$$

Here S_h is the strain noise power spectral density, T_{dat} is the data live time, and Θ is a statistical threshold factor which depends on the parameter space and other details of the data analysis pipeline. For a coherent multi-interferometer search, the limits add in inverse quadrature. In previous wide parameter-space \mathcal{F} -statistic searches [4], Θ was somewhat below 30. Monte Carlo simulations searching for injected signals indicate that Θ is in the mid-30s for this type of search, and thus we use 35 in our estimates below. Because Θ is determined by the tail of a gaussian distribution, it is very weakly dependent on the volume of parameter space searched. However the data live time T_{dat} is computationally limited and thus does depend on the parameter space.

The parameter space range is chosen as follows: The frequency band is chosen to be 100–300 Hz, roughly the band over which we can beat the indirect limit. The frequency derivative ranges are chosen based on considering braking indices in the range 2–6. This range covers all known pulsars, except the Vela pulsar which is visibly interacting with its wind nebula (nonexistent for Cas A). It also includes the values for dipole-dominated and quadrupole-dominated radiation (3 or 5), plus allowing for changes in multipoles on timescales comparable to the age of the star. Thus the range of each frequency derivative depends on the lower derivatives, and we have

$$100 \text{ Hz} \leq f \leq 300 \text{ Hz}, \quad f/(5\tau) \leq -\dot{f} \leq f/\tau, \quad 2\dot{f}^2/\tau \leq \ddot{f} \leq 6\dot{f}^2/f. \quad (9)$$

There remains the problem of efficiently tiling, or choosing specific points in parameter space for which to compute the \mathcal{F} -statistic. It is straightforward to apply the method of [29] to find

the parameter space metric [30]

$$\gamma_{jk} = \frac{4\pi^2 T_{\text{span}}^{j+k+2} (j+1)(k+1)}{(j+2)!(k+2)!(j+k+3)}, \quad (10)$$

where the components are with respect to the k th derivative of the GW frequency (and f_0 is the frequency itself) at the beginning of the observation and T_{span} is the total duration of data (including dropouts). This metric, which is the Fisher information matrix with a phase constant projected out, is used to set up an efficient tiling which takes advantage of the covariances between parameters. The number of points needed for an optimal (bcc or A_3^*) tiling is given by [31]

$$N_p \simeq \frac{5\sqrt{5}}{72} \mu^{-3/2} \sqrt{\det \gamma} f_{\text{max}}^3 / \tau^3, \quad (11)$$

where μ is the mismatch and we have performed the integral in Eq. (24) of [31] using the ranges (9) and discarding the smaller bounds which are small corrections. We determine the highest frequency derivative needed by finding k such that $\gamma_{kk} \Delta_k^2 > \mu$, where Δ_k is the range of the k th frequency derivative and we take μ to be 20% (typical for periodic signal searches). In our case \ddot{f} is required for T_{span} greater than about a week, i.e. any search which can beat the indirect limit.

Finally we estimate the computational cost and sensitivity of the search. Preliminary runs on nodes of the APAC cluster [32] find a timing of about 6×10^{-7} s per node per SFT. Assuming 30-minute SFTs and two interferometers with 70% duty cycle, the computing time for the search (exclusive of Monte Carlo simulations to compute upper limits) is

$$16 \text{ days} \left(\frac{f_{\text{max}}}{300 \text{ Hz}} \right)^3 \left(\frac{300 \text{ yr}}{\tau} \right)^3 \left(\frac{T_{\text{span}}}{12 \text{ days}} \right)^7 \left(\frac{200}{\text{nodes}} \right). \quad (12)$$

For $T_{\text{span}} = 12$ days and two interferometers with the initial LIGO design noise spectrum [33], the sensitivity curve (8) bottoms out at

$$8.0 \times 10^{-25} \left(\frac{f_{\text{max}}}{300 \text{ Hz}} \right)^{3/14} \left(\frac{300 \text{ yr}}{\tau} \right)^{3/14} \quad (13)$$

and is plotted in Figure 1. Thus we see that this search for Cas A, when completed on S5 data, will beat the indirect limit on GW emission from about 100 to 300 Hz. This will double the number of objects (after the Crab pulsar) for which initial LIGO has beaten an indirect limit.

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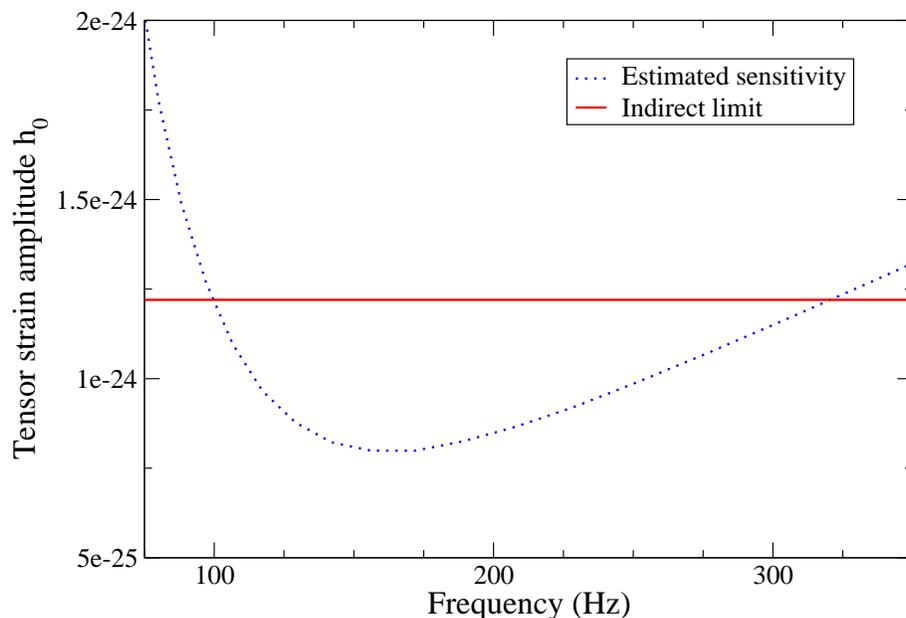


Figure 1. Estimated sensitivity of an S5 search compared to the indirect limit on GW emission for Cas A. Search parameters are the fiducial ones described in the text.

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