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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 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 LIGO's current S5 data. Cas 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 (GW): searches for known pulsars [1–3], a search for the non-pulsing low-mass X-ray binary Sco X-1 [4], and all-sky searches for as yet unknown neutron stars [4–6]. The first and last of these are approaching close to the indirect upper limits on gravitational wave emission inferred from the observed rate of spindown, or increase of pulse period of pulsars, as well as population arguments for Galactic distributions of neutron stars [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 frequency and frequency evolution are not known at all. Here 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 S5 data 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 [7]. 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 this object 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 it is an active pulsar [8]. 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) [8; 9]. Only in the first scenario could GW be detectable by LIGO. What makes Cas A attractive is its youth: The stars with the highest indirect limits on gravitational radiation are all young (see next section), and one could argue on theoretical grounds that any deformations left over from the violent birth of the star have had less time to smooth away by mechanisms such as viscoelastic creep.

For the purpose of a directed search for gravitational waves from the CCO in Cas A, we need to know the object's right ascension and declination. Chandra has obtained these to subarcsecond accuracy ($\alpha = 23\text{h}23\text{m}(27.945 \pm 0.05)\text{s}$, $\delta = 58°48'(42.51 \pm 0.4)''$ [8]), 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 ± 0.4 kpc [10]. Extrapolation of the proper motions of outer ejecta knots suggest a convergence date of 1681 ± 19, consistent with a possible observation by Flamsteed in 1680 [7]. Thus we take 330 years as our canonical age estimate. In what follows we use the canonical neutron star moment of inertia of 10^{45} g cm^2, although modern equations of state predict values higher for most neutron stars by a factor 2 or 3 [11].

3. Indirect limits

We derive an indirect limit of the gravitational wave emission from periodic sources by assuming that the gravitational wave luminosity

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

is equal to the time derivative of the total rotational kinetic energy

$$-\left(\frac{dE}{dt}\right)_{\text{rot}} = -\frac{d}{dt}\left(\frac{1}{2}\pi^2 I_{zz} f^2\right) \tag{2}$$

where ϵ is the ellipticity, I_{zz} the principal moments of inertia, assumed constant, and f the gravitational wave frequency [4; 12; 13]. Combined with the gravitational wave strain

$$h = \frac{4\pi^2 G}{c^4} \frac{I_{zz} \epsilon f^2}{d} , \tag{3}$$

where d is the distance of the source [4; 14], we find independent expressions for the upper limits on

$$h \le \frac{1}{d}\sqrt{\frac{5GI_{zz}}{2c^3}\frac{-\dot{f}}{f}} , \qquad \epsilon \le \sqrt{\frac{5c^5}{32\pi^4 G I_{zz}}\frac{-\dot{f}}{f^5}} ; \tag{4}$$

For Cas A, the frequency f and its evolution $\dot{f}$ are unknown; the ratio $\dot{f}/f$ is, however, related to the characteristic age of the source by

$$\tau = \frac{1}{n-1}\frac{f}{-\dot{f}}\left(1 - \left(\frac{f}{f_0}\right)^4\right) \tag{5}$$

where n is the braking index (and is equal to 5 for gravitational waves) and $f_0 \ggg f$, i.e. we assume that the source has spun down from a much higher initial frequency [4; 13]. Thus,

$$\tau \approx \frac{f}{-4\dot{f}}, \tag{6}$$

and substituting into the upper limits gives

$$h_{\rm age} \leq \frac{1}{d}\sqrt{\frac{5GI_{zz}}{8c^3\tau}}\,, \qquad\qquad \epsilon_{\rm age} \leq \sqrt{\frac{5c^5}{128\pi^4 G I_{zz}\tau f^4}}\,; \tag{7}$$

Note that the assumption that the source has spun down is no longer needed, but we do need to assume that the star is still in the LIGO band. For Cas A, using the numbers from the previous section we get

$$h_{\rm age} \leq 1.2\times 10^{-24}\left(\frac{3.4\ \rm kpc}{d}\right)\sqrt{\left(\frac{I}{10^{45}\ \rm g\ cm^2}\right)\left(\frac{300\ \rm yr}{\tau}\right)} \tag{8}$$

$$\epsilon_{\rm age} \leq 3.7\times 10^{-4}\left(\frac{100\ \rm Hz}{f}\right)^2\sqrt{\left(\frac{10^{45}\ \rm g\ cm^2}{I}\right)\left(\frac{300\ \rm yr}{\tau}\right)}. \tag{9}$$

Some theories of quark matter allow for ellipticities this high, though normal neutron star models do not [15–17]. An internal magnetic field of order 10^{16} G could also produce such ellipticities [18], although it is not clear if such a field is stable [19], and if the external field is this strong then the star by now has spun down out of the LIGO frequency band. 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 fully-coherent [1; 4] and semi-coherent [5; 6; 20] methods to search for periodic gravitational waves. These methods trade off between sensitivity and computational cost.

For Cas A the integration time needed is short enough (see next section) for us to be able to take 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 [21]. This routine computes optimal filters for the gravitational wave signal in the frequency domain, using short Fourier transforms (SFTs) of segments of strain data from the interferometers, which are treated as a coherent network [22].

The search uses data from the 4km LIGO interferometers at Hanford, WA, and Livingston, LA. The gravitational wave strain data is in the form of short Fourier transforms or SFTs [4] generated from 30-minute segments of data. this length is chosen so that the gravitational wave frequency will remain in one frequency bin over the length of the SFT. The SFTs are vetoed by a suite of data quality flags to remove poorer quality SFTs. For windows of up to 15 days (see next section) during the first year of the S5 run, the ratio of remaining SFT live time to clock time (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) lattice, which is known to be the optimal lattice covering in three dimensions [23].

In the event no gravitational waves are found, we will set upper limits by Monte Carlo simulations searching for a multitude of software-injected signals in the data. These signals will have a distribution of amplitudes, inclination angles, and polarization angles in each frequency bin, allowing us to set confidence limits for a realistic population of sources. We will also test on a smaller set of simulated signals which were hardware injected into the S5 data. This is similar to previous LSC procedures to set upper limits.

5. Estimated cost and sensitivity

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

$$h_{95\%} = \Theta\sqrt{S_h(f)/T_{\rm dat}}. \tag{10}$$

Here S_h is the strain noise power spectral density, $T_{\rm dat}$ 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. Our 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 only weakly dependent on the volume of parameter space searched. However the data live time $T_{\rm dat}$ 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 roughly 100–300 Hz, centered on the region of lowest instrument noise. (It is also roughly the band over which we can beat the indirect limit.) The frequency derivative ranges are chosen based on considering braking indices $f\ddot{f}/\dot{f}^2$ 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. For each frequency we thus want to search values of $-\dot{f}$ ranging from $f/(5a)$ to f/a, and for each f and $\dot{f}$ we search values of $\ddot{f}$ ranging from $2\dot{f}^2/f$ to $6\dot{f}^2/f$.

There remains the problem of efficiently tiling, or choosing specific points in parameter space for which to run the $\mathcal{F}$-statistic. It is straightforward to apply the method of [24] to find the parameter space metric components [25]

$$\gamma_{jk} = \frac{(2\pi f)^2 T^{j+k+2}}{(j+2)(k+2)(j+k+3)}, \tag{11}$$

where the parameters f_k are related to the GW frequency derivatives by

$$f_k = \frac{k!}{f}\frac{d^k f}{dt^k} \tag{12}$$

and f itself (at some fiducial time) is f_0. This metric, which is essentially the 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) tiling is given by [26]

$$N_p = \frac{\sqrt{5}}{128}\mu^{-3/2}\sqrt{\gamma(f_{\rm max})}\prod_k \Delta f_k, \tag{13}$$

where Δf_k is the range of f_k and we have modified his formula to account for changing the metric at different frequencies. We find the highest frequency derivative needed by finding k such that $\gamma_{kk}\Delta f_k^2$ is greater than the mismatch, i.e. the discretization-induced loss of power signal-to-noise ratio which we take here to be 30% (typical for periodic signal searches). In our case for integration times greater than a week, the second frequency derivative is required.

Our preliminary runs on the APAC cluster find a cost of about 1×10^{-6} s per node per SFT. For 300 nodes we get a cost of

$$4\ \text{days}\left(\frac{f_{\rm max}}{300\ \text{Hz}}\right)^3\left(\frac{330\ \text{yr}}{a}\right)^3\left(\frac{T}{10\ \text{days}}\right)^7. \tag{14}$$

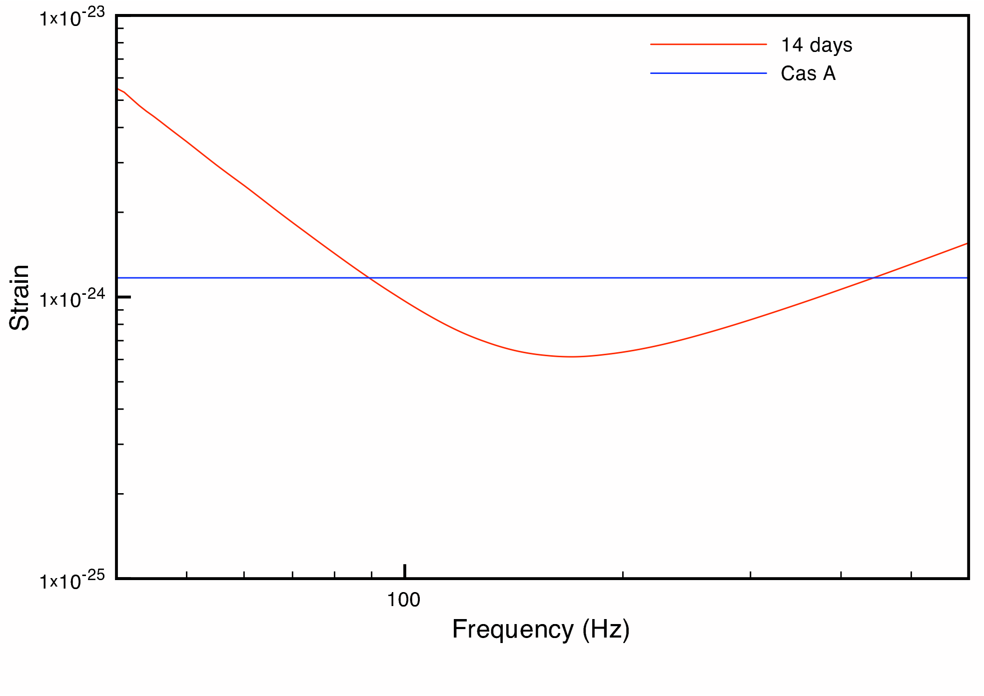

Figure 1. Estimated sensitivity of a 2-week S5 search compared to the indirect limit for Cas A.

Inverting that, we find that for 60 days computer time we can afford

$$T = 15 \text{ days} \left(\frac{300\text{ Hz}}{f_{\max}}\right)^{3/7} \left(\frac{a}{330\text{ yr}}\right)^{3/7}. \tag{15}$$

If we assume two interferometers and a 70% duty cycle, the sensitivity curve bottoms out at

$$7 \times 10^{-25} \left(\frac{f_{\max}}{300\text{ Hz}}\right)^{3/14} \left(\frac{320\text{ yr}}{a}\right)^{3/14} \tag{16}$$

and is plotted in Figure 1.

Thus we see that this search, when completed, will beat the all-sky search and will also beat the indirect limit on GW emission from about 100–300 Hz. Cas A thus doubles the number of objects (after the Crab pulsar) for which initial LIGO can beat the indirect limit.

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