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BEATING THE SPIN-DOWN LIMIT ON GRAVITATIONAL WAVE EMISSION FROM THE CRAB PULSAR

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ABSTRACT

We present direct upper limits on gravitational wave emission from the Crab pulsar using data from the first nine months of the fifth science run of the Laser Interferometer Gravitational-wave Observatory (LIGO). These limits are based on two searches. In the first we assume that the gravitational wave emission follows the observed radio timing, giving an upper limit on gravitational wave emission that beats indirect limits inferred from the spin-down and braking index of the pulsar and the energetics of the nebula. In the second we allow for a small mismatch between the gravitational and radio signal frequencies and interpret our results in the context of two possible gravitational wave emission mechanisms.

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1. INTRODUCTION

The Crab pulsar (PSR B0531+21, PSR J0534+2200) has long been regarded as one of the most promising *known* local sources of gravitational wave emission and is an iconic target for gravitational wave searches (Press & Thorne 1972; Zimmermann 1978). Its high spin-down rate, $\dot{\nu} \approx -3.7 \times 10^{-10}\,\mathrm{Hz\,s^{-1}}$, corresponds to a kinetic energy loss rate of $\dot{E} = 4\pi^2 I_{zz} \nu |\dot{\nu}| \approx 4.4 \times 10^{31}\,\mathrm{W}$ (using a spin frequency of $\nu = 29.78\,\mathrm{Hz}$ and the canonical value of $10^{38}\,\mathrm{kg\,m^2}$ for the principal moment of inertia I_{zz}.) This loss is due to a variety of mechanisms, including magnetic dipole radiation, particle acceleration in the magnetosphere, and gravitational radiation. If one assumes that all the energy *is* being radiated gravitationally, the gravitational wave tensor amplitude at Earth is

$$h_0^{\mathrm{sd}} = \left(\frac{5}{2} \frac{G I_{zz} |\dot{\nu}|}{c^3 r^2 \nu} \right)^{1/2}, \tag{1}$$

where r is the distance to the pulsar (Abbott et al. 2007c). For the Crab pulsar this "spin-down upper limit" is $h_0^{\mathrm{sd}} = 1.4 \times 10^{-24}$, using the canonical moment of inertia and a distance $r = 2\,\mathrm{kpc}$. It has long been known that the Laser Interferometer Gravitational-wave Observatory (LIGO) can achieve this sensitivity by integrating several months of data with the initial design noise spectrum.

The electromagnetic emission and accelerating expansion of the Crab Nebula are powered almost entirely by the rotation of the pulsar. The question now is whether these two loss mechanisms can account for the vast majority of the observed rotational energy loss, or whether gravitational wave emission has a significant part to play.

The bolometric luminosity of the nebula is 1–2×10^{31} W, which accounts for less than half the spin-down power (e.g., Davidson & Fesen 1985). There have been many attempts to estimate the power involved in the observed acceleration of optical filaments, for example recently by Bejger & Haensel (2002, 2003). However these depend on poorly known factors such as the mass and expansion history of the nebula, and the uncertainties in the estimated power are comparable to the spin-down power itself. Thus electromagnetic observations of the nebula, within their uncertainties, still allow for a substantial fraction of the spin-down power to be emitted in gravitational waves.

The braking index $n = \nu\ddot{\nu}/\dot{\nu}^2$ of the pulsar further constrains the gravitational wave emission. The observed value $n = 2.5$ still is not well understood on theoretical grounds, but since quadrupolar radiation has $n = 5$ it implies that only a small fraction of the spin-down power is emitted in gravitational waves. The best estimate in print is by Palomba (2000), who uses a phenomenological model of the spin-down (present and historical) together with the present braking index and known age of the pulsar to estimate that the highest possible h_0 today is about 40% of the spin-down limit. This value is consistent with the observations of the nebula, and is also observable with several months of S5 data.

The first directed search for gravitational waves from the Crab pulsar was performed in the early 1970s using a 30 m interferometer giving a strain upper limit of 3×10^{-17} by Levine & Stebbins (1972). Later, specially designed bar detectors with resonant frequencies of around 60 Hz (Hirakawa et al. 1978) were used, which gave a gravitational wave energy flux upper limit of $14\,\mathrm{W\,m^{-2}}$, corresponding to to an amplitude of approximately $h_0 \leq 1.8\times10^{-19}$. A similar bar was used in 1993 to give an upper limit that was still over an order of magnitude away from the spin-down limit (Suzuki 1995). Data from the LIGO detectors have improved upon these bar results. The LIGO second science run (S2) produced a 95% degree-of-belief upper limit of $h_0^{95\%} = 4.1 \times 10^{-23}$ (Abbott et al. 2005), and the combined data from the S3 and S4 runs produced an upper limit of $h_0^{95\%} = 3.1\times10^{-24}$ (Abbott et al. 2007c). These were approximately 30 and 2.2 times greater than the spin-down limit respectively.

In this Letter, we describe searches of data from the fifth LIGO science run (S5), which started on 2005 November 4 and ended on 2007 October 1 (Abbott et al. 2007b). During this period the detectors (the 4 km and 2 km detectors at LIGO Hanford Observatory, H1 and H2, and the 4 km detector at the LIGO Livingston Observatory, L1) were at their design sensitivities and had duty factors of 78% for H1, 79% for H2, and $\sim 66\%$ for L1. The GEO600 detector (Lück et al. 2006) also participated in the S5 run but was much less sensitive at the frequency of the expected signal.

The Crab pulsar was observed to glitch on 2006 August 23 at approximately 04:00 UTC (Lyne et al. 2007; Lyne 2006). Since the glitch mechanism is not certain, it may involve unpredictable changes in the gravitational wave timing and amplitude, and therefore this glitch is a natural point at which to pause this coherent search for the Crab pulsar. Our data set consists of H1 and H2 data from 2005 November 4 and L1 data from 2005 November 14 up to 2006 August 23. For the two different searches carried out in this analysis, described below, this gives 201, 222 and 158 days of data for H1, H2 and L1 respectively for the single-template search, and 182, 206, and 141 days of data for H1, H2 and L1 respectively for the multi-template frequency-frequency first derivative search, which required larger contiguous segments than the single-template search.

2. METHODS

We use two different methods (see Abbott et al. 2004) to search for gravitational waves from the Crab pulsar to account for different emission scenarios. One method uses a single time domain template for the gravitational wave signal assuming that the gravitational wave period evolves precisely as the electromagnetic pulse period. The other method works in the frequency domain to cover a relatively small, physically motivated range of frequency and spin-down values. The searches use the known frequency and position of the Crab pulsar, as derived from the Jodrell Bank Crab Pulsar Monthly Ephemeris (Lyne et al. 2007). Both searches assume that emission will be at or near twice the pulsar's spin frequency, $2\nu = \nu_{\mathrm{GW}} \sim 59.56\,\mathrm{Hz}$, which is the frequency of emission by a steadily rotating quadrupolar deformation, i.e. a triaxial star. The Crab might be emitting through an r-mode (Owen et al. 1998) if the mode saturates at a small amplitude and thus is long-lived (e.g., Brink et al. 2005). If so, $\nu_{\mathrm{GW}} \approx 4\nu/3$ minus a correction dependent on the equation of state of the star. The uncertainty of the correction to the Crab's frequency is of order one part in 10^3 (Lindblom et al. 1999). Due to this relatively large uncertainty and the greater instrument noise at this frequency, we elected not to search for $\nu_{\mathrm{GW}} \approx 4\nu/3$. Although 2ν is close to the 60 Hz power line frequency, it is sufficiently far away that the searches are relatively unaffected by non-stationary components of the power line noise. The absolute timing accuracy of the LIGO data is sufficiently good that the likelihoods produced for each detector can be combined to give a joint likelihood.

For a given search frequency and spin-down, the four unknown signal parameters are the gravitational wave amplitude h_0, the initial phase ϕ_0, the spin-axis inclination angle ι, and the polarization angle ψ. We first present results assuming that we have no prior information about any of these parameters and therefore use uniform priors over their allowable ranges. However, X-ray observations of the Crab Pulsar Wind Nebula provide values of the orientation angle ι and polarisation angle ψ of the pulsar. From Ng & Romani (2004, 2008) we use $\iota = 62.17 \pm 2.195^\circ$ and $\psi = 125.155 \pm 1.355^\circ$, where we have taken the mean of the best fit values for the outer and inner tori of the nebula. We use these ranges to put Gaussian priors on these two parameters for both the search techniques.

The single-template search (Dupuis & Woan 2005) assumes a triaxial star emitting gravitational waves at precisely twice the spin frequency, following the electromagnetic pulse phase evolution and taking into account the small variations in phase caused by timing noise (Pitkin & Woan 2007). It uses a standard Bayesian methodology to produce a joint posterior probability volume over the four unknown parameters using data from all three detectors. As stated above we will use both uniform priors and restricted priors on ψ and ι when calculating the posterior. We can marginalise the angle parameters to produce a posterior probability for h_0 and from this calculate a 95% degree-of-belief upper limit on the gravitational wave amplitude.

A search is also performed at gravitational wave frequencies $\nu_{\rm GW}$ close to, but not equal to, 2ν. We use simple astrophysical arguments to pick out a range of plausible search frequencies. We begin by writing the fractional frequency splitting as $1+\delta$, so that

$$\nu_{\rm GW} = 2\nu(1+\delta), \tag{2}$$

where δ is a small number. A relation of this form holds if the gravitational waves are produced by a component spinning separately from the electromagnetically emitting one, with the two components linked by some torque which acts to enforce co-rotation between them on a timescale $\tau_{\rm coupling}$. In such a case $\delta \sim \tau_{\rm coupling}/\tau_{\rm spin-down}$, where $\tau_{\rm spin-down} \sim \nu/\dot{\nu} \simeq 2500$ years. A relation of the form of equation (2) also holds if the gravitational waves are produced by free precession of a nearly biaxial star (Jones & Andersson 2002). In such a case $\delta \sim \alpha(I_{zz} - I_{xx})/I_{xx}$ where α is some factor of order unity that depends upon the geometry of the free precession e.g. the wobble angle (the angle between z-axis and angular momentum axis.) It should be noted that no clear signature of free precession has been seen in the radio pulsations of the Crab pulsar, so this is perhaps a less plausible frequency splitting mechanism, although precession would have little effect upon the radio signal if the amplitude of the precession were small.

Together, these scenarios suggest searching over a frequency interval $\pm\Delta\nu_{\rm GW}$ centred on 2ν, where $\Delta\nu_{\rm GW} \sim |\delta|\,2\nu$. We have chosen to follow such a strategy, using a maximum value of $|\delta| = 10^{-4}$. In terms of the two-component model, such a $|\delta|$ value corresponds to $\tau_{\rm coupling} \sim 10^{-4}\,\tau_{\rm spin-down} \sim$ several months, comparable to the longest timescales seen in glitch recovery where re-coupling between the two components might be expected to occur. In terms of free precession, $|\delta| = 10^{-4}$ is on the high end of the level of deformation that the solid phases of compact objects are thought to be capable of sustaining (Owen 2005).

Using the above estimates as a guide, a band of frequencies $\pm 6 \times 10^{-3}$ Hz centred on twice the Crab pulsar's observed frequency was searched over. Corresponding bands in frequency derivatives were motivated via differentiation of equation (2), which together with the assumption that δ itself evolves no more rapidly than on the spin-down timescale, leads to a band in frequency first derivative of $\pm 1.5 \times 10^{-13}$ Hz/s, with searches over higher derivatives being unnecessary.

The search method is a maximum likelihood technique, the coherent multi-detector F-statistic derived in Cutler & Schutz (2005). An explicit search is required over a single sky position and second derivative of the frequency, and over the selected ranges of the frequency and of the first frequency derivative. The spacing of the templates is chosen in such a way as to ensure at most a 5% loss in the detection statistic, resulting in a total of 3×10^7 templates. The detection statistic $2F$ is computed for each template. The expected 3σ range of the largest $2F$ value for Gaussian noise (no signal present) and 3×10^7 templates is 35 to 49. The largest $2F$ value found in the actual search is 37, well within the expected range for noise.

Based on the largest $2F$ value, 95% confidence upper limits are produced using a frequentist Monte Carlo injection method, as described in Abbott et al. (2007a). For the unknown parameters uniform distributions and physically informed distributions were used for the injected population of signals, consistent with the choices made for the single-template time domain search.

3. RESULTS

In the single-template search the joint (i.e. multi-detector) posterior probability distribution for the gravitational wave amplitude peaks at zero, indicating that no signal is visible at our current sensitivity. The joint 95% upper limit on the gravitational wave amplitude, using uniform priors on all the parameters, is $h_0^{95\%} = 3.5{\times}10^{-25}$ (also see Table 1.) Given in terms of the pulsar's ellipticity (Abbott et al. 2007c) via

$$\varepsilon = 0.237 \left(\frac{h_0}{10^{-24}}\right)\left(\frac{r}{1\,{\rm kpc}}\right)\left(\frac{1\,{\rm Hz}}{\nu}\right)^2\left(\frac{10^{38}\,{\rm kg\,m^2}}{I_{zz}}\right) \tag{3}$$

this is $\varepsilon = 1.9{\times}10^{-4}$, using the canonical I_{zz} and $r = 2\,{\rm kpc}$. This is 4.1 times lower than the spin-down upper limit given by equation (1). This is also 1.7 times lower than the limit estimated by Palomba (2000) (see §1.)

This limit can be recast in terms of the percentage of the power radiated via gravitational waves compared to the total power available from spin-down. Squaring the ratio of the spin-down and direct upper limit shows that less than $\approx 6\%$ of the total power is being emitted as gravitational waves, assuming the canonical moment of inertia (see final column of Table 1.)

Using the restricted priors on ψ and ι we get an upper limit 1.25 times smaller than that with uniform priors (see Table 1.) This would restrict the energy budget of gravitational waves from the Crab pulsar to be less than 4% of the spin-down energy available.

With the coherent multi-template frequency-frequency first derivative search we set a 95% confidence upper limit of 1.7×10^{-24} over the entire parameter space searched. Using equation (3) to determine an upper limit on the ellipticity gives $9.0{\times}10^{-4}$. These upper limits are larger than the time single template search limits by roughly a factor of five. This is to be expected because the larger number of templates raises the number of trials and thus the statistical confidence threshold.

Assuming restricted priors on ψ and ι yields an improved upper limit of $1.2{\times}10^{-24}$, a factor of 1.2 below the spin-down limit, across the entire parameter space searched.

The upper limits in Table 1 are subject to uncertainty in the calibration of the detectors. Amplitude calibration uncertainties for H1, H2 and L1, respectively, are: 8.1%, 7.2% and 6.0% (ST analysis), and 9.5%, 7.8% and 8.7% (MT analysis).

4. DISCUSSION

TABLE 1
Upper limits on gravitational wave amplitude for the single-template (ST) and multi-template (MT) searches with uniform and restricted priors on the pulsar orientation

	$h_0^{95\%}$	ellipticity	$h_0^{\rm sd}/h_0^{95\%}$	$P_{\rm gw}/P_{\rm sd}$
ST uniform	3.5×10^{-25}	1.9×10^{-4}	4.1	6%
ST restricted	2.8×10^{-25}	1.5×10^{-4}	5.1	4%
MT uniform	1.7×10^{-24}	9.0×10^{-4}	0.8	156%
MT restricted	1.2×10^{-24}	6.5×10^{-4}	1.2	73%

Under the assumption that the gravitational wave and the electromagnetic signals are phase-locked, our single-template search results constrain the gravitational wave contribution to the observed spin-down luminosity to be less than 6%. This beats the indirect limits inferred from all electromagnetic observations of the Crab pulsar and nebula.

Our upper limits are interesting because they have entered the outskirts of the range of theoretical predictions. Normal neutron stars are believed to be mostly fluid with maximum elastic deformations orders of magnitude smaller than the few times 10^{-4} of our upper limits, but some theories of quark matter predict solid or mostly solid stars which could sustain such ellipticities (Owen 2005; Lin 2007; Haskell et al. 2007). However, our upper limits do not constrain the composition of the star and cannot constrain any fundamental properties of quark matter. The ellipticity is proportional to the quadrupolar strain, which may simply be very low for a given star no matter its composition. The Crab is likely to have an ellipticity at least about 10^{-11} due to the stresses of its internal magnetic field (Cutler 2002) if the internal field is comparable to the external dipole of 4×10^{12} G. Our upper limits can be interpreted as direct upper limits of about 10^{16} G on the internal magnetic field, depending on the ratio of toroidal to poloidal components (Colaiuda et al. 2008).

As discussed in Abbott et al. (2007c) there is considerable uncertainty in the true value of the Crab pulsar's moment of inertia. The best guesses at its value come from neutron star equation of state models rather than direct measurements. Previous pulsar ellipticity upper limits and spin-down limits have made use of the canonical value of I_{zz}. We can however cast our upper limit in a way that makes no assumptions about the moment of inertia, by placing the limit on the neutron star quadrupole moment $\approx I_{zz}\varepsilon$. This then allows us to plot the single-template search results as exclusion regions in the I-ε plane. The results, with uniform and restricted prior ranges, are plotted in this way in Figure 1. Our upper limits are smaller than the spin-down limit by a factor that varies as $I_{zz}^{1/2}$. If we take the theoretical upper bound on the moment of inertia to be $3\times10^{38}\,{\rm kg\,m^2}$ as in (Abbott et al. 2007c) then the result with uniform priors beats the spin-down limit by a factor of 7.1.

Finally, the physical interpretation of our multi-template search depends upon the assumed cause of the splitting $\nu_{\rm GW} = 2\nu(1+\delta)$ between gravitational and electromagnetic signals. In the context of the two-component spin-down model, our results show that a

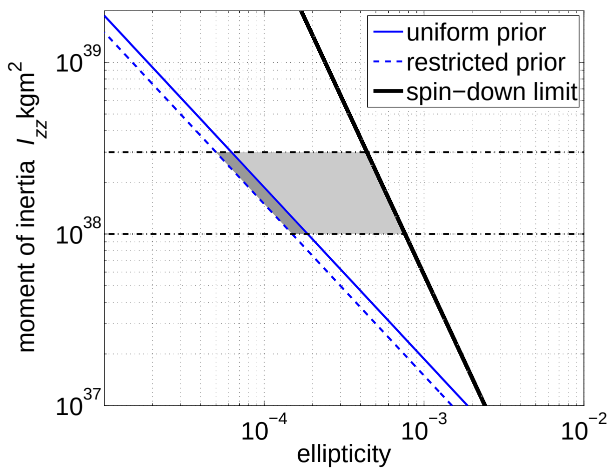

Fig. 1.— The single template search upper limits from S5, for the uniform and restricted prior ranges, and spin-down upper limit plotted as exclusion regions in a moment of inertia–ellipticity plane. Areas to the right of the diagonal lines are excluded. The dashed horizontal lines represent estimates of the theoretical lower and upper bounds of acceptable moments of inertia at 1–$3\times10^{38}\,{\rm kg\,m^2}$. The shaded area represents the region that is newly excluded with these results.

gravitational wave emitting component of the star coupled to the electromagnetic (radio) emitting component on a timescale of a few months or less has a quadrupole asymmetry $I_{yy}-I_{xx}$ of no more than $9.0\times10^{34}\,{\rm kg\,m^2}$. This is about five times larger than the bound on $I_{yy}-I_{xx}$ obtained in the single-template search. If free precession is responsible for the frequency splitting our results instead give an upper limit on the product $\Delta I\sin^2\theta$, where ΔI is the $I_{zz}-I_{xx}$ part of the quadrupole moment tensor that participates in the precession and θ the wobble angle (Jones & Andersson 2002).

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