How photon astronomy affects searches for continuous gravitational waves

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Abstract
Due to their computational limitations, searches for continuous gravitational waves (GW) are significantly more sensitive when informed by observational photon astronomy and theoretical astrophysics. Indirect upper limits on GW emission inferred from photon astronomy indicate which objects are more interesting for GW searches, and also set sensitivity milestones which GW searches need to beat to be considered GW astronomy. How GW results are interpreted depends on previous indirect limits and the theory of astrophysical GW emission mechanisms. I describe the interplay between these issues for the four types of continuous GWs searches, and show how photon astronomers can help the growing field of GW astronomy now and in the near future.

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1. Introduction

The theme of the last two gravitational wave data analysis workshops has been connecting gravitational waves (GW) to existing astronomy and astrophysics. The most commonly discussed connection is between ground-based GW detectors and observations of electromagnetic counterparts of short-lived GW signals (binary inspirals or less-modeled bursts) [1]. But searches for continuous GW (with ground-based detectors this means rapidly rotating neutron stars) are even more closely connected to photon astronomy: Most searches for continuous waves are computationally limited, and thus their sensitivity substantially benefits from information on where to look, even more than inspiral and burst signals. As a result, we who search for continuous GW divide neutron stars into four types, determined mainly by what is already known about them. For each type of neutron star, photon astronomy also sets indirect upper limits on GW emission—milestones which GW searches must beat to begin doing GW astronomy. Theory has a role too: where we look depends on our understanding of GW emission mechanisms, and our interpretation of our observational results depends on emission mechanisms and existing indirect limits. While continuous GW searches present
more expensive data analysis problems than other GW searches, the fact that makes them expensive—the billions of GW cycles per year—means that they carry very precise information on their sources and can reveal much about neutron star astrophysics and the physics of matter at supernuclear densities [2, 3].

Here, I review present and near-future LIGO searches for continuous GWs and place them in their astronomical and astrophysical context. I skip over most details of the data analysis, which are described in the observational papers [4–13] and references therein. I describe the four types of continuous GW searches, sensitivities, emission mechanisms and the indirect limits that set sensitivity milestones. I focus on issues related to detecting signals rather than extracting information from them; the latter are summarized elsewhere [2, 3].

2. Four types of searches

For the purposes of continuous GW searches, there are four types of neutron stars: known pulsars (such as the Crab), previously unknown neutron stars, non-pulsing non-accreting neutron stars (such as the central compact object in Cas A), and accreting neutron stars (such as in Sco X-1). Thus, I divide continuous GW searches into four corresponding types: targeted searches with a known timing solution, all-sky surveys, directed searches for non-accreting stars and directed searches for accreting stars (where the orbit and accretion raise extra analysis issues). This division is made on the basis of differing GW search sensitivities (strongly affected by what is already known from photon astronomy), different indirect upper limits on GW emission and different emission mechanisms. In this section, I describe the first and last factors, and I describe the second in later sections devoted to each type of search.

2.1. Sensitivity

It is easier to find something if you know where to look, and continuous GWs are no exception. This can be seen by comparing observational upper limits on GW strain for different types of searches—a recent all-sky search [10] was almost an order of magnitude less sensitive in amplitude than a known pulsar search of comparable LIGO data [7], or two orders of magnitude in GW luminosity (see below).

There are two contributions to the difference: fully coherent methods (such as matched filtering) accumulate amplitude signal-to-noise ratio as $T^{1/2}$, where $T$ is the live time of data integrated. Thus a 95% confidence upper limit on strain tensor amplitude $h_0$ takes the form

$$h_0^{95\%} = \Theta \sqrt{S_h/T}, \quad (1)$$

where $S_h$ is the strain power spectral noise density of the detector at the GW frequency. (The generalization to multiple detectors is straightforward but lengthy; see [14] for the matched filtering version.)

The threshold factor $\Theta$ is determined by the statistics (effective number of independent trials in parameter space) and efficiency of the search (coverage of the parameter space) and is the first major contribution to the difference. For known pulsars, i.e. with coherent timing solutions and precise sky locations obtained from photon astronomy, $\Theta$ is about 11 [4] averaged over sky locations and inclination and polarization angles. For the Cas A search underway, which is directed at a single sky location but must cover many possible timings, $\Theta$ should be in the mid-30s [15].

The second contribution to the difference arises because computational cost can scale very steeply with $T$, especially when searching many sky locations as in all-sky surveys; and thus the coherent integration time in the denominator of (1) is limited. Semi-coherent methods...
combine $N$ short (live time $T_{coh}$) coherently integrated stretches of data incoherently, i.e. by adding power not amplitude. This makes the computation much cheaper, but improves signal-to-noise only as $N^{1/4} = (T/T_{coh})^{1/4}$ (for $N$ more than a few). Thus for a single detector the sensitivity takes the form

$$h_{0}^{95\%} = \Theta \sqrt{S_h (T_{coh} T)^{-1/4}} = \Theta \sqrt{S_h N^{-1/4} T_{coh}^{-1/2}},$$

(2)

where for all-sky all-inclination searches the threshold factor $\Theta$ is in the mid-20s [10]. (Appendix B of that reference shows how semi-coherent $\Theta$ factors are typically lower than for comparable searches, e.g., 8 instead of 11 for known pulsars.)

### 2.2. Emission mechanisms

I reviewed continuous GW emission mechanisms fairly recently [16] and space in this article is limited. Therefore here I briefly summarize the main issues and mention only some recent results which are most relevant to present continuous GW searches and future searches of accreting neutron stars. (Specifically I neglect free precession and deformations due to internal toroidal magnetic fields as well as most of the $r$-mode story.)

The most interesting mechanism at the moment is rotation of a static quadrupolar deformation, which can be thought of as a mountain (although the most important part is generally buried). The important number is the equatorial ellipticity

$$\epsilon = (I_{xx} - I_{yy})/I_{zz},$$

(3)

where $I_{ab}$ is the moment of inertia tensor and $z$ is the rotation axis. This dimensionless $\epsilon$ is roughly the $\ell = m = 2$ mass quadrupole moment normalized to the moment of inertia, or (if the star had uniform density) the height of the quadrupolar deformation in terms of stellar radius. (Radiation from $\ell > 2$ and $\ell = 2, m = 1$ is somewhat suppressed.) Then the GW strain tensor amplitude is

$$h_0 = (2\pi f)^2 I_{zz} \epsilon / D,$$

(4)

where $D$ is the distance to the star, the GW frequency is $f = 2/P$ in terms of the spin period $P$, and I have used geometrized units.

The maximum theoretically predicted ellipticity depends on the composition of the star: for a normal neutron star (thin solid crust on a liquid interior) the highest possible is of order $10^{-6}$ [17]. For hybrid stars with partly solid cores due to a baryon-quark or baryon-meson phase transition spread over a range of densities, the highest is of order $10^{-5}$ [18]. For quark stars, which in some cases are predicted to be mostly solid, the ellipticity could be $10^{-3}$ or more [18–21]. The maximum ellipticity can be written schematically (neglecting the integral) as

$$\epsilon_{\text{max}} = \text{breaking strain} \times \text{shear modulus} \times \text{geometry}. $$

(5)

The last factor, which depends on the bulk equation of state and treatment of hydrostatic equilibrium, is uncertain by a factor of a few (as seen by properly comparing [17] to older results). The shear modulus is the main reason for the orders of magnitude variation between models, as it increases rapidly with density and thus is highest in exotic phases which are solid at the highest densities, e.g. [22]. The breaking strain has also been considered uncertain by orders of magnitude, with most $\epsilon_{\text{max}}$ results quoting a highest value of $10^{-2}$ (roughly the maximum seen on Earth). However recent simulations [23] indicate that neutron star crust, due to the great pressure, is a nearly perfect crystal with breaking strain of order $10^{-1}$. Then the maximum ellipticity of a normal neutron star is ten times higher ($10^{-5}$), and if the effect holds for exotic cores the other maximum ellipticities are also ten times higher.
A separate issue is how to drive $\epsilon$ toward $\epsilon_{\text{max}}$. In young neutron stars, it is not clear what would cause large sustained elastic deformations or how long they would last, although the violence and asymmetry of the supernova explosion may help with the former. But for accreting neutron stars, there are several mechanisms to drive and sustain asymmetry (which must exist as shown by x-ray pulses and burst oscillations). Lateral temperature gradients due to non-spherical accretion flow affect electron capture rates and thereby effectively lift denser material in hotter regions (see [24] and references therein). On the surface, the magnetic field will funnel incoming accreted material onto the magnetic poles, e.g. [25] and references therein. Accretion can also, through a complicated set of physical effects briefly surveyed in parts of [3], sustain the $r$-modes (Coriolis-dominated fluid oscillations) of a neutron star. In this case, the continuous GW frequency is $f P \approx 4/3$ rather than $f P = 2$, and $h_0$ is a function of mode amplitude rather than static ellipticity. ($R$-modes may also be active for a time in young neutron stars.)

3. Known pulsars

With a precise timing solution and sky location, a pulsar’s spin frequency, frequency evolution (including glitches and timing noise) and Doppler shifts due to the detectors’ motion and pulsar’s binary motion (if any) are all known and can be de-modulated. Then it is computationally feasible to coherently integrate the entire data set—S5, the longest so far [26] is about two calendar years of LIGO data (one year triple coincidence between three detectors)—to achieve the optimal signal-to-noise ratio and make the most of this hard-won data.

With $f P = 2$, the current LIGO low-frequency cutoff of 40 Hz means that pulsars with $P < 50$ ms are of interest; and with advanced LIGO (and Virgo) this will extend to $P < 200$ ms [27, 28]. (All searches so far have assumed $f P \approx 2$, but future searches will also investigate $f P \approx 4/3$ and $f P \approx 1$.) Thus we are looking for young fast pulsars and recycled millisecond pulsars, but not garden-variety pulsars, rotating radio transients, anomalous x-ray pulsars or soft gamma repeaters. At the moment, there are almost 200 known pulsars in the LIGO band, or about 10% of the total [29].

For known pulsars the common indirect limit on GW emission is based on the observed spin-down. Given the observed period and spin-down (period derivative), the assumption that all the spin-down is due to GW emission sets a robust upper limit on $h_0$. That limit is found (for a static $m = 2$ quadrupole) to be

$$h_0^{sd} = 4.5 \times 10^{-24} \left( \frac{1 \text{kpc}}{D} \right) \left( \frac{l_z}{10^{45} \text{ g cm}^2} \right)^{1/2} \left( \frac{10^1 \text{ yr}}{P/\dot{P}} \right)^{1/2}.$$  \hspace{1cm} (6)

Due to uncertainties in the moment of inertia and the distance, this limit is uncertain typically by a factor of 2. The highest spin-down limit in the current LIGO band is for the Crab pulsar, with fiducial value $h_0^{sd} = 1.4 \times 10^{-24}$. The Vela pulsar has a comparable $h_0^{sd}$ and will be in the band of advanced LIGO and Virgo. A search for Vela in Virgo data, although not yet at full sensitivity, is underway.

Of course the true GW emission is less than the spin-down limit; and if we know other things about the pulsar we can set limits on how much less. The emission of the pulsar itself is typically less than 1% of the spin-down luminosity, but for young pulsars associated with a pulsar wind nebula we can subtract off the bolometric luminosity of the nebula (which may be tens of per cent). In some cases, the second period derivative or equivalently braking index is known; and then a stricter indirect limit can be computed using a phenomenological model
of the star’s spin-down history [30]. For the pulsars examined, this limit on \(h_0\) is a few times stricter than the spin-down limit.

The spin-down limit on \(h_0\) corresponds to an ellipticity upper limit

\[
\epsilon_{sd} = 1.1 \times 10^{-4} \left( \frac{I_{zz}}{10^{45} \text{ g cm}^2} \right) \left( \frac{10^3 \text{ yr}}{P/\dot{P}} \right)^{1/2} \left( \frac{P}{10 \text{ ms}} \right)^2. \tag{7}
\]

For young pulsars, this limit is typically of order \(10^{-4}\) or higher (for the Crab it is \(7 \times 10^{-4}\)), while for recycled millisecond pulsars it can be \(10^{-10}\) or lower.

The first LIGO continuous-wave search [4] of the first science data run (S1) focused on a single pulsar, J1939+2134. (At the time it was the most rapidly rotating known pulsar, thus maximizing \(h_0\) for a given ellipticity.) The next search was expanded to 28 pulsars in S2 data [5]. The author list includes not only the LIGO Scientific Collaboration (LSC) but Michael Kramer and Andrew Lyne, radio astronomers who obtained timing data crucial to the sensitivity of the search. With the combined S3 and S4 data set the total rose to 78 pulsars [7], and again Kramer and Lyne were co-authors for obtaining crucial pulsar timing. The best upper limit on \(h_0\) from the S3/S4 search was \(3 \times 10^{-25}\) for a pulsar near the minimum of the noise spectrum using several weeks each of S3 and S4 data. All of these searches employ fully coherent methods, since for known pulsars they are computationally feasible.

Most recently the LSC published a search [11] of the first 9 months of S5 for the Crab pulsar which beat the spin-down limit and the stronger indirect limits from the braking index and luminosity of the pulsar wind nebula. The best upper limit on GW emission—which also takes advantage of the inclination of the pulsar spin axis inferred from x-ray images of the nebula—was \(h_0 = 3 \times 10^{-25}\) or about 4% of the canonical spin-down luminosity, beating the tightest indirect limit on \(h_0\) (from the braking index) by a factor of 2. Also included was a broader search allowing for a possible difference between the radio timing and GW signal behavior, motivated by the possibility that GW and photon emission might come from separate components of the star and by the fact that glitches indicate the existence of multiple components rotating at (sometimes) different rates. The energy upper limit of this latter search was more than an order of magnitude worse than the former search due to the effects of searching over many possible timings.

The best ellipticity upper limit on the Crab was \(1 \times 10^{-4}\), within the range possible for stars with crystalline quark cores. It is very interesting that this is below \(\epsilon_{\text{max}}\) for various exotic matter models. However, I must correct a misconception [19, 20] which is spreading [21] that LIGO upper limits are constraining QCD parameters: a GW upper limit on \(\epsilon\) does not constrain anything unless it beats \(\epsilon_{sd}\) (not done until the Crab search [11]), and even then it only constrains \(\epsilon\) of that star (a function of its history) rather than \(\epsilon_{\text{max}}\) (a function of universal properties of dense matter): \(\epsilon\) may be much less than \(\epsilon_{\text{max}}\) simply because the actual strain (as opposed to the breaking strain) is very small. Constraints will only come with many more observations beating spin-down limits as well as work on mountain building theory [18].

At the time of writing, a search of all available S5 data for the Crab and more than 100 other pulsars is nearing completion, and will be published by the LSC and Virgo Collaboration with several more radio and x-ray astronomer co-authors. Coherent timing solutions provided by the latter were crucial for making the most of the GW data. Not all of the pulsars in the LIGO/Virgo band are included due to a lack of coherent timing solutions across the S5 run for some pulsars.

The GW collaborations are eager to obtain timing for every pulsar in band, especially those with spin-down limits near what is achievable. Values of \(h_{0}^{\text{sd}}\) can be inferred from the ATNF catalogue [29] and compared to the generic pulsar sensitivity estimate (1) assuming one year of triple coincident data at present or advanced noise levels. Due to varying angles...
and the intrinsic randomness of the noise, this sensitivity estimate is uncertain at about the factor of 2 level characteristic of the spin-down limits. Therefore even pulsars with fiducial spin-down limits within about a factor of 3 of (1) are extremely interesting. (The others are still interesting in the case of extreme luck, such as the dispersion-measure distance being badly overestimated.) With present data, the most interesting pulsars after the Crab are J0537−6910, J1952+3252 and J1913+1011. Later this year LIGO is scheduled to start another long science run (enhanced LIGO) with strain noise amplitude reduced by about 2 [31], and Virgo is scheduled for an enhanced run on a similar timescale. In the era of advanced LIGO (strain noise an order of magnitude lower than S5 data) more than 70 fiducial spin-down limits will be beatable by (1), and of order 100 will be close to it.

4. Unknown neutron stars

Most of the neutron stars in the galaxy are not seen via any form of photons, but they may still emit continuous GWs. We must then search over the whole sky, the frequency band of the detectors, and possible frequency evolutions of the sources; and even using every computer on the planet still could not coherently integrate a year’s worth of data in a year. Thus, we need to use semi-coherent data analysis methods which trade off computational cost for sensitivity.

Even for the many unseen neutron stars in the galaxy, we can place an indirect limit on \( h_0 \). The original version of this limit was due to Blandford in the 1980s (unpublished), but has reappeared several times in the literature, most recently in [8]. With a galactic neutron star birth rate \( R \) derived from supernova observations and an infinite planar spatial distribution, the supernova-based indirect limit (which is a statistical statement about the brightest source) is

\[
 h_{0}^{SN} = 4 \times 10^{-24} (R \times 30 \text{ yr}),
\]  

completely independent of the typical ellipticity. A more recent treatment [32] based on realistic spatial distributions of neutron stars produces a more complicated result, which does depend on the typical ellipticity. The highest values of \( h_{0}^{SN} \) are about \( 1 \times 10^{-24} \) for an extremely optimistic but not a priori impossible set of assumptions.

The most basic all-sky continuous GW survey was a fully coherent matched filtering search of 10 h of LIGO S2 data [8]. Semi-coherent searches were published for S2 [6] and recently for S4 [10], both using several weeks of data with a coherent integration time of half an hour. The best strain upper limit from the latter was \( 4 \times 10^{-24} \) (averaging over inclinations as in the known pulsar limits from comparable data), more than an order of magnitude in amplitude (i.e., two orders in luminosity) worse than the best S3/S4 known pulsar limit of \( 3 \times 10^{-25} \) [7]. Also, the all-sky searches used much more computing power than the known pulsar search, again illustrating the advantages of knowing where to look. The S4 all-sky searches (three were reported in [10]) nonetheless achieved a sensitivity comparable to Blandford’s indirect limit. The S4 searches also achieved non-trivial range milestones, as described and plotted toward the end of that paper.

More recently, the most sensitive all-sky search to date was published on several months of the early S5 data [13], again with a half-hour coherent integration time. This search placed upper limits on GW emission (\( h_0 \) as low as about \( 1 \times 10^{-24} \) for an average inclination) ruling out the most extreme versions of the improved supernova indirect limit [32]. Another version of this search on a greater fraction of S5 data is underway, and is expected to yield even greater sensitivity.

The ultimate solution to the computational limitation of the all-sky searches is Einstein@Home [33], a distributed computing project involving tens of thousands of users and otherwise idle computers from around the world. This enormous computing power allows
the coherent integration time to be increased to more than a day, which is still small compared to the months of coherent integration for known pulsars. Recently a search of S4 data was published [12] demonstrating the power of Einstein@Home, although that search was not designed to place upper limits. Since that search, Einstein@Home has been running improved searches on S5 data, the first of which was recently accepted for publication [34].

All these all-sky surveys have searched for isolated neutron stars. However, plans are being made to search for unseen neutron stars in binaries, such as faint quiescent low-mass x-ray binaries, after data analysis algorithms are further developed to handle the extra challenge of searching over unknown binary parameters.

5. Non-pulsing non-accreting neutron stars

For some non-accreting neutron stars the position is known, but the spin frequency and its evolution are unknown. The prototype is the central compact object in supernova remnant Cas A. With some knowledge of where to look in parameter space, the sensitivity of such searches should be intermediate between those for known pulsars and unseen neutron stars.

For these neutron stars, we do not know the spin-down and thus cannot use the spin-down limit. However, if we make the same physical assumption, that the spin-down is dominated by quadrupolar GW emission, and additionally assume that this has always been so (and that $I_{zz}$ has remained constant), we obtain an indirect strain limit based on the age $a$,

$$h_{0}^{\text{age}} = 2.3 \times 10^{-24} \left(\frac{1 \text{ kpc}}{D}\right) \left(\frac{I_{zz}}{10^{45} \text{ g cm}^2}\right)^{1/2} \left(\frac{10^{3} \text{ yr}}{a}\right)^{1/2}. \quad (9)$$

The highest such limit which is well determined is for Cas A at $1.2 \times 10^{-24}$ [15]. The corresponding ellipticity limit is $4 \times 10^{-4} - 4 \times 10^{-5}$ over the frequency band 100–300 Hz. There is one big caveat not present with known pulsar searches: we have to hope that the GW emission is in the LIGO/Virgo band, which is true only for about 10% of all known pulsars, and a smaller fraction of young isolated pulsars.

The Cas A search underway [15], the first of this kind, is fully coherent over 12 days of LIGO S5 data and covers the frequency band 100–300 Hz and many values of $\dot{f}$ and $\ddot{f}$. It should beat $h_{0}^{\text{age}}$ over that band, with the best $h_{0}^{95\%}$ about $8 \times 10^{-25}$ at the minimum of $S_{h}$, and cost more than the known pulsar searches but substantially less than all-sky surveys. This will add to the very short list of objects where a GW search (continuous-wave or otherwise) has beaten an indirect limit from photon astronomy.

There are many interesting possibilities beyond Cas A [35]. Several other supernova remnants are inhabited by similar non-pulsing objects. ‘Empty’ supernova remnants and pulsar wind nebulae are also attractive places to do this type of GW search, as long as they are not too large or too old. (With too many sky positions, the sensitivity of the search will not beat the all-sky surveys, and with older objects the neutron star may have been kicked far enough to be hard to find.) Massive star forming regions are also good targets for hunting young neutron stars, and globular clusters with dense cores are attractive places to look for older neutron stars which have been effectively rejuvenated by close encounters. Directed searches are being planned for all these targets, and work is also in progress on more sensitive data analysis techniques (e.g. [36]) which will prove especially fruitful for this type of search.

6. Accreting neutron stars

Accreting neutron stars may be the best continuous GW sources because they are driven toward the maximum asymmetry, whether ellipticity or $r$-mode. These stars are most likely
to emit continuous GWs at the indirect limit, but that limit is lower than for other types: for accreting neutron stars the indirect limit is derived by assuming that accretion spin-up and GW spin-down are in equilibrium, and thus the most rapidly accreting stars (i.e., those in low-mass x-ray binaries) are the most interesting. Taking the observed x-ray flux $F_x$ as a proxy for the accretion rate, we have for a neutron star of mass $M$ and radius $R$

$$h_0^{\text{acc}} = 3 \times 10^{-27} \left( \frac{F_x}{10^{-8} \text{ erg cm}^{-2} \text{ s}^{-1}} \right)^{1/2} \left( \frac{R}{10 \text{ km}} \right)^{3/4} \times \left( \frac{1.4 M_\odot}{M} \right)^{-1/4} \left( P \times 300 \text{ Hz} \right)^{1/2} \left( 1 \text{ yr} \right)$$

(10)

assuming emission from ellipticity [24]. (For an $r$-mode $h_0^{\text{acc}}$ is about 1.5 times greater at fixed $P$.) The highest such limit is for Sco X-1 at $3 \times 10^{-26}$ (for the fiducial parameters), which is still two orders of magnitude lower than the largest indirect limits on continuous GW emission for the other types of neutron stars.

The LSC has published two searches for Sco X-1 so far. The fully coherent search of S2 data [8] was restricted to only 6 h of data, while the semi-coherent S4 search [9] used several weeks of data divided into 1 min coherent intervals. The latter search obtained a best upper limit on $h_0$ of $3 \times 10^{-24}$, more than two orders of magnitude weaker than the indirect limit. The coherent integration time is much shorter than that for Cas A primarily due to uncertainties in orbital parameters, and on longer timescales the stochasticity of accretion torque would also come into play.

In contrast to the other types of continuous GW searches, no searches for accreting neutron stars are underway. This is because the indirect limits will be accessible only with advanced LIGO and Virgo. The widespread impression to the contrary is due to the fact that the limits would be accessible with a known timing solution. In general, the highest indirect limits are for the few ‘bright Z’ sources accreting near the Eddington limit. Unfortunately, these are also the sources for which the spin frequency is completely unknown, complicating the GW data analysis. And the accreting stars with best timing information have the lowest average accretion rates and thus indirect GW limits that are too low even with the advantages of known timing [24].

However in the long run, accreting neutron stars may be the best prospects for GW detection rather than upper limits, because of numerous mechanisms through which accretion can drive the asymmetry needed to emit GWs. Therefore, the LSC and Virgo collaboration are designing better data analysis techniques, for example, based on the frequency comb used in radio pulsar searches [37]. It is also important to consider astrophysical models beyond the strict torque-balance scenario: torques might be balanced only on average over long timescales, with GW active and quiescent episodes; and during the former, the GW signal could be stronger than $h_0^{\text{acc}}$ [38]. Upper limits can then constrain such scenarios.

7. Present and future observational interactions

I close by summarizing the ways that observational photon astronomy is already helping continuous GW searches and can do so in the future.

The most sensitive continuous GW searches are for known pulsars. It is imperative for the ground-based GW detection collaborations to maintain and expand links to the pulsar timing community, ideally obtaining timing for all pulsars in the LIGO/Virgo band during the data runs. Discovery of more pulsars in the band with high spin-downs will also be extremely helpful, with radio projects culminating in the Square Kilometer Array expected to expand the list of known pulsars by an order of magnitude. Sensitive, frequent, and flexible x-ray timing
(such as provided by the aging Rossi X-ray Timing Explorer satellite) is also important as the only way to obtain up-to-date parameters on PSR J0537-6910, one of the most interesting (glitchy, high spin-down limit) pulsars. As shown by the LIGO Crab result [11], studies of pulsar wind nebulae revealing the inclination angle can also improve the sensitivities of GW searches.

Discoveries of new non-pulsing neutron stars will add interesting targets to the list of directed searches, which are more sensitive than all-sky surveys. It is helpful to find spin periods, which move these objects to the category of known pulsars—as long as the spin period is short enough for $2/P$ to be in the LIGO/Virgo band. Other observations (e.g., to better determine ages and distances) of existing objects will help rank targets in terms of indirect limits on GW emission. For this purpose, it is also helpful to find pulsar wind nebulae (with or without a compact object), which are correlated with high spin-downs.

Several years from now, searches for continuous GWs from accreting neutron stars will reach interesting sensitivities. They would be aided greatly by determination of spin periods of bright $Z$ sources, as well as by continued timing of accreting millisecond pulsars and spin (and orbital) period estimates from burst oscillations.

Last but certainly not least, anyone can help the all-sky surveys by running Einstein@Home screensaver [33], which now searches Arecibo radio data for new pulsars as well.

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References

[1] Abbott B et al 2008 Astrophysically triggered searches for gravitational waves: status and prospects Class. Quantum Grav. 25 114051
[2] Owen B J 2009 Probing neutron stars with gravitational waves arXiv:0903.2603 (a white paper for the Astro2010 decadal survey)
[3] Sathyaprakash B S and Schutz B F 2009 Physics, astrophysics and cosmology with gravitational waves Living Rev. Rel. 12 2
[4] Abbott B et al 2004 Setting upper limits on the strength of periodic gravitational waves using the first science data from the GEO 600 and LIGO detectors Phys. Rev. D 69 082004
[5] Abbott B et al 2005 Limits on gravitational wave emission from selected pulsars using LIGO data Phys. Rev. Lett. 94 181103
[6] Abbott B et al 2005 First all-sky upper limits from LIGO on the strength of periodic gravitational waves using the Hough transform Phys. Rev. D 72 102004
[7] Abbott B et al 2007 Upper limits on gravitational wave emission from 78 radio pulsars Phys. Rev. D 76 042001
[8] Abbott B et al 2007 Coherent searches for periodic gravitational waves from unknown isolated sources and Scorpius X-1. Results from the second LIGO science run Phys. Rev. D 76 082001
[9] Abbott B et al 2007 Upper limit map of a background of gravitational waves Phys. Rev. D 76 082003
[10] Abbott B et al 2008 All-sky search for periodic gravitational waves in LIGO S4 data Phys. Rev. D 77 022001
[11] Abbott B et al 2008 Beating the spin-down limit on gravitational wave emission from the Crab pulsar Astrophys. J. 683 L45–50
[12] Abbott B et al 2009 The Einstein@Home search for periodic gravitational waves in LIGO S4 data Phys. Rev. D 79 022001
[13] Abbott B et al 2009 All-sky LIGO search for periodic gravitational waves in the early S5 data Phys. Rev. Lett. 102 111102
[14] Cutler C and Schutz B F 2005 The generalized F-statistic: multiple detectors and multiple GW pulsars Phys. Rev. D 72 063006
[15] Wette K et al 2008 Searching for gravitational waves from Cassiopeia A with LIGO Class. Quantum Grav. 25 235011
[16] Owen B J 2006 Detectability of periodic gravitational waves by initial interferometers Class. Quantum Grav. 23 S1–8
[17] Haskell B, Jones D I and Andersson N 2006 Mountains on neutron stars: accreted versus non-accreted crusts Mon. Not. R. Astron. Soc. 373 1423–39
[18] Owen B J 2005 Maximum elastic deformations of compact stars with exotic equations of state Phys. Rev. Lett. 95 211101
[19] Lin L-M 2007 Constraining crystalline color superconducting quark matter with gravitational-wave data Phys. Rev. D 76 081502
[20] Haskell B, Andersson N, Jones D I and Samuelson L 2007 Are neutron stars with crystalline color-superconducting cores relevant for the LIGO experiment? Phys. Rev. Lett. 99 231101
[21] Knippel B and Sedrakian A 2009 Gravitational radiation from crystalline color-superconducting hybrid stars Phys. Rev. D 79 083007
[22] Mannarelli M, Rajagopal K and Sharma R 2007 The rigidity of crystalline color superconducting quark matter Phys. Rev. D 76 074026
[23] Horowitz C J and Kadau K 2009 The breaking strain of neutron star crust and gravitational waves Phys. Rev. Lett. 102 191102
[24] Watts A, Krishnan B, Bildsten L and Schutz B F 2008 Detecting gravitational wave emission from the known accreting neutron stars Mon. Not. R. Astron. Soc. 389 839–68
[25] Vigeland M and Melatos A 2009 Improved estimate of the detectability of gravitational radiation from a magnetically confined mountain on an accreting neutron star Mon. Not. R. Astron. Soc. 395 1972–894
[26] Abbott B et al 2009 LIGO: the Laser Interferometer Gravitational-Wave Observatory Rep. Prog. Phys. 72 076901
[27] Advanced LIGO team, Advanced LIGO Reference Design LIGO Technical report M060056 (can be found at https://dcc.ligo.org)
[28] Acernese F et al 2008 Virgo status Class. Quantum Grav. 25 184001
[29] Manchester R N, Hobbs G B, Teoh A and Hobbs M 2005 The Australia telescope national facility pulsar catalogue Astron. J. 129 1993–2006
[30] Palomba C 2000 Pulsars ellipticity revised Astron. Astrophys. 354 163–8
[31] Adhikari R, Fritschel P and Waldman S (Enhanced LIGO) Technical report T060156 (can be found at http://admdbsrv.ligo.caltech.edu/dcc/)
[32] Knispel B and Allen B 2008 Blandford’s argument: the strongest continuous gravitational wave signal Phys. Rev. D 78 044031
[33] http://einstein.phys.uwm.edu
[34] Abbott B P et al 2009 Einstein@Home search for periodic gravitational waves in early S5 LIGO data Phys. Rev. D arXiv:0905.1705 (at press)
[35] Owen B J et al Targets for directed searches for continuous gravitational waves, in preparation
[36] Patel P, Siemens X and Dupuis R Implementation of barycentric resampling for continuous wave searches in gravitational-wave data Technical report T090003 (can be found at http://admdbsrv.ligo.caltech.edu/dcc/)
[37] Messenger C and Woan G 2007 A fast search strategy for gravitational waves from low-mass X-ray binaries Class. Quantum Grav. 24 S469–80
[38] Watts A L and Krishnan B 2009 Detecting gravitational waves from accreting neutron stars Adv. Space Res. 43 1049–54