Interesting astrophysics from initial LIGO data: searching for isolated non-pulsing neutron stars

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Summary

The LIGO gravitational wave observatories have now collected over a year of data at better than design sensitivity [LIGO]. They are at the threshold of being able to detect gravitational waves from persistent sources such as spinning neutron stars. We are beginning a search for gravitational waves from isolated non-pulsing neutron stars, starting with the supernova remnant Cassiopeia A.

Why is this interesting?

From the perspective of gravitational waves, isolated neutron stars can be divided into three broad categories:

- Pulsars where the sky position, the frequency and its time derivatives are known to usable precision, e.g. the Crab;
- As yet undiscovered stars where no information is known, which might be found by all-sky broadband searches;
- Non-pulsing stars where the sky position is already known, requiring only a search over the frequency and its time derivatives.

In this last category, Cas A has the highest known upper limit on the amplitude of the gravitational waves, and is thus the best known candidate for possible detection in initial LIGO data.

How large are the waves?

We can estimate the amplitude of the gravitational waves we expect for Cas A, assuming it to be a spinning neutron star with a non-axisymmetric distortion [Prix]. In this case we can write the gravitational wave luminosity as

$$L_{\mathrm{GW}} = 1.4\times10^{36}\left(\frac{h_0}{10^{-24}}\right)^2\left(\frac{f}{100\,\mathrm{Hz}}\right)^2\left(\frac{d}{10^4\,\mathrm{ly}}\right)^2 \mathrm{erg/s},$$

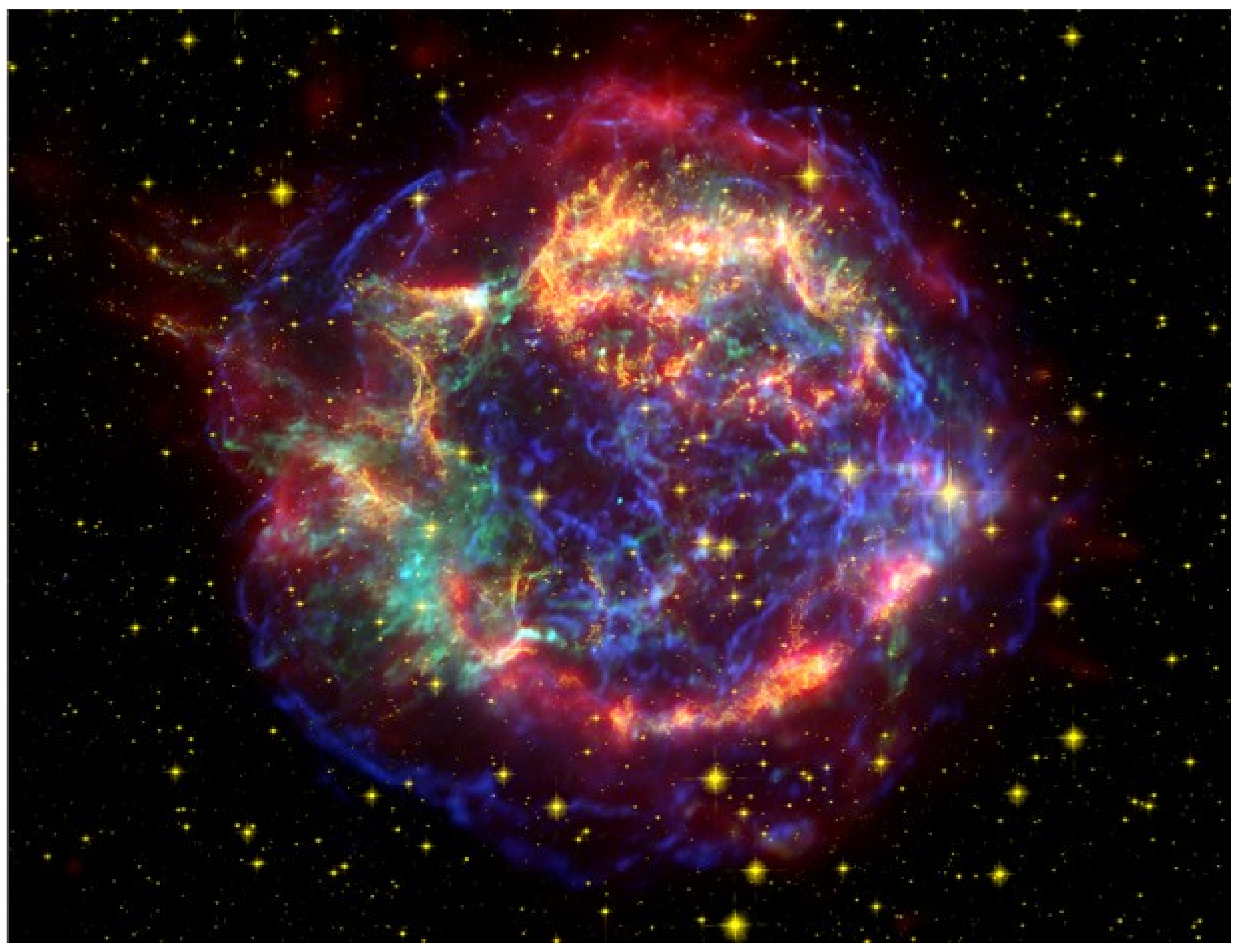
where h_0 is the dimensionless amplitude of the gravitational waves, f is the rotation frequency of the neutron star and d the distance to it. If we assume that the gravitational wave emission is being completely powered by the rotational energy of the neutron star, the upper limit on the gravitational wave amplitude is

$$h_0 \leqslant 1.4\times10^{-24}\left(\frac{10^4\,\mathrm{ly}}{d}\right)\sqrt{\left(\frac{300\,\mathrm{yr}}{\tau}\right)\left(\frac{I_{zz}}{10^{45}\,\mathrm{g\,cm^2}}\right)},$$

where τ is the age and I_{zz} the principal moment of inertia of the neutron star; fiducial values are for Cas A.

How do we search for them?

The output of a interferometric gravitational wave detector is essentially a noisy audio signal $x(t)$ with a range of 50 Hz to approximately 7 kHz. The optimal method of isolating a possible gravitational wave signal from a persistent source,



A composite image of Cas A in infra-red (red), optical (yellow) and X-ray (blue, green) [CasA]. Detecting gravitational waves from Cas A would be akin to "hearing" what this picture sounds like.

e.g. from Cas A, is by matched filtering, also known as maximum likelihood [JKS]. We assume the evolution of the gravitational wave frequency to be of the form

$$f(t) \approx f_0\left(1 + f_1 t + f_2 t^2\right);$$

the initial frequency f_0 and the parameters f_1, f_2 characterising its time derivatives are unknown. We construct templates $h(t, f_0, f_1, f_2)$ of the expected gravitational wave signal and compute the detection statistic

$$F = (x\|h) - \frac{1}{2}(h\|h),$$

where $(\cdot\|\cdot)$ denotes an inner product weighted by noise. A search for Cas A over two weeks of initial LIGO data from two detectors would need to consider $\sim10^{12}$ points (f_0, f_1, f_2) across a three-dimensional parameter space

$$f_{\mathrm{L}} \leqslant f_0 \leqslant f_{\mathrm{H}},\ -\frac{1}{\tau} \leqslant f_1 \leqslant 0,\ -\frac{1}{\tau^2} \leqslant f_2 \leqslant 0,$$

the computational cost of which is roughly

$$4800\,\frac{f_{\mathrm{H}}^3 - f_{\mathrm{L}}^3}{(200\,\mathrm{Hz})^3}\,\mathrm{CPU\ days}.$$

Such a search would surpass the upper limit on the gravitational wave amplitude given above by about a factor of two.

What could we get out of it?

Successful detection of gravitational waves from Cas A would, for example, allow the determination of the ellipticity ϵ, a measure of the non-axisymmetric distortion of the neutron star, from h_0 and f. This in turn would constrain possible exotic equations of state of the neutron star, e.g. solid strange, hybrid quark-baryon or charged meson condensate stars [Owen].

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