Quaking Neutron Stars

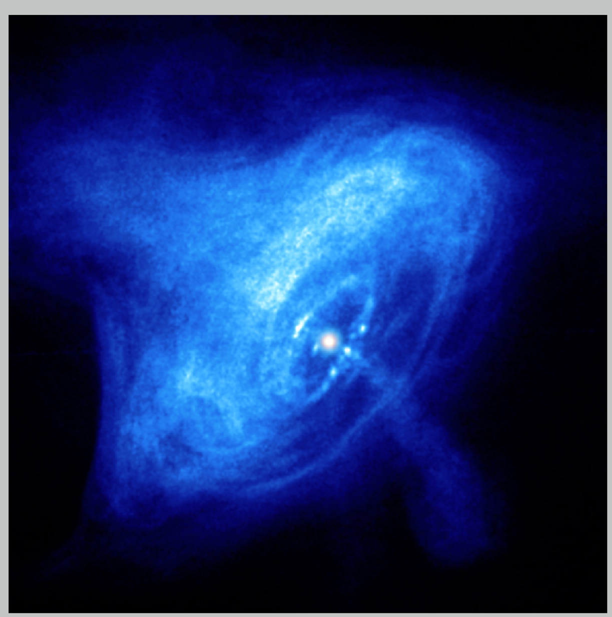
Lucy Keer
Supervisor: Ian Jones

University of Southampton

Overview: Some neutron stars occasionally undergo a sudden increase in their rotation rate – a **glitch.** We investigate a model in which this is caused by a cracking of the neutron star crust, and discuss how this can be used to estimate **gravitational wave emission** from the glitch.

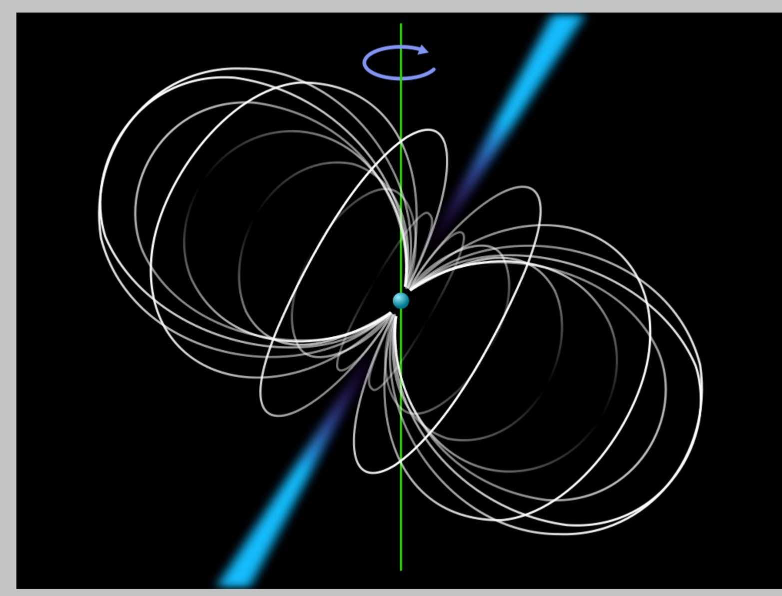
1. A new star?

In 1045, Chinese astronomers saw a new 'star' appear in the sky. The new light source was bright enough to be visible in the day, but faded away after a few months. We now know that this was actually a supernova – a massive star collapsing under its own gravity. The shock wave from this explosion can still be seen (*right*), and is known as the Crab Nebula.



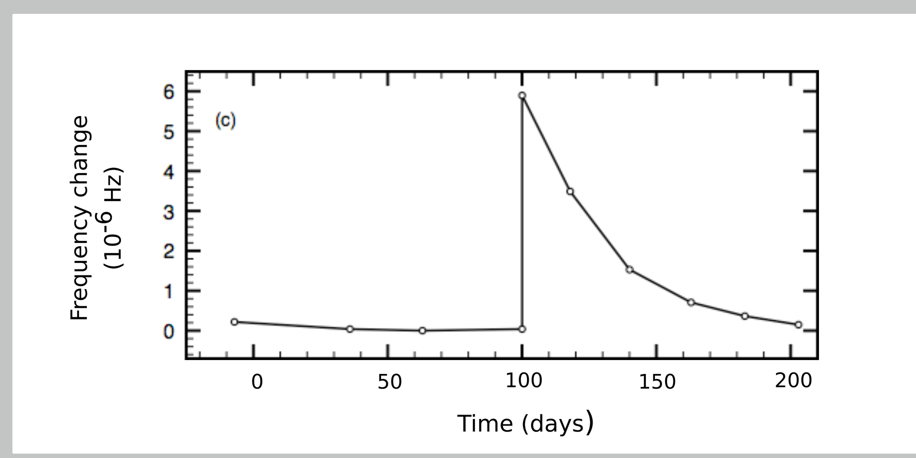
The nebula is not just seen in visible light: it can also be observed in other parts of the electromagnetic spectrum. This X-ray image (*left*) shows a single bright source in the centre of the nebula: the Crab Pulsar. This is a neutron star, the collapsed remnant of the original star left after the supernova explosion. This star is hugely compressed – a mass one or two times that of the Sun is contained in a ten kilometre radius.

2. Glitching neutron stars



We can also view the Crab Pulsar in the radio spectrum – in fact, this is how neutron stars were first discovered. A strong 'lighthouse beam' of radiation (*right*) sweeps past the Earth as the star rotates, showing that the pulsar spins around 30 times a second.

The radio pulses from neutron stars are extremely regular, with the only major change being a very gradual slowdown as the star loses energy over time. Once this effect is accounted for, most pulsars keep time to one part in 10^{11} or better.

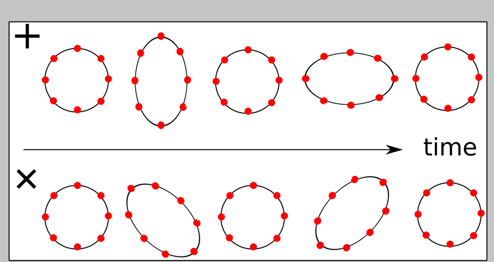


However, young neutron stars, such as the Crab Pulsar, can sometimes exhibit more erratic behaviour. The most dramatic of these effects is a sudden sharp increase in the pulsar spin rate, called a glitch.

The figure above shows a typical glitch in the Crab Pulsar. Similar glitches happen every few years.

3. Why are we interested in glitches?

To produce this increase in spin rate, the internal structure of the neutron star must undergo a very sudden change. This means that glitches are a good candidate for producing gravitational waves, a prediction of Einstein's theory of general relativity.



One of the central lessons of this theory is that no signal travels faster than the speed of light. Any disturbances in the gravitational field of a massive, compact object, such as a neutron star, should therefore take time to reach a distant observer.

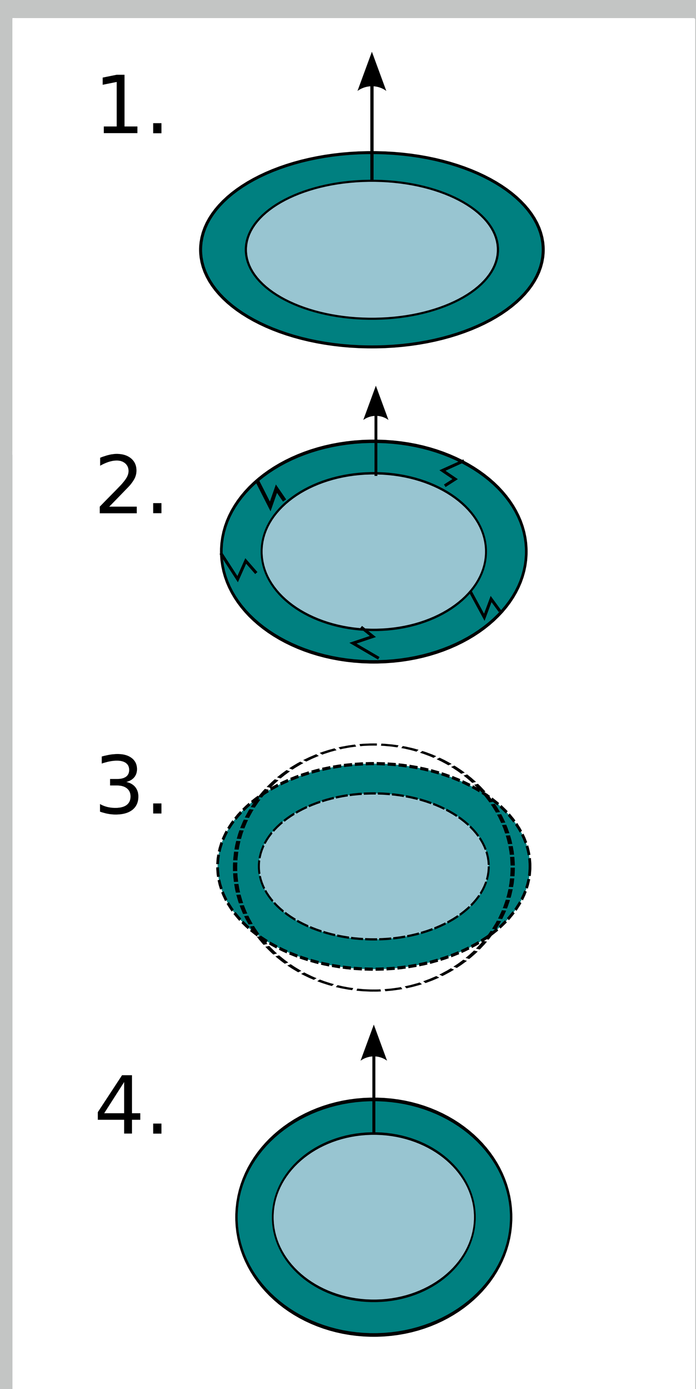
We can detect these propagating disturbances by observing the distinctive patterns of changes they cause in the distance between objects. The figure (*above*) gives a (very exaggerated) depiction of what happens to a circle of particles as a gravitational wave passes.

In reality, the size of this effect is extremely small, and is yet to be detected directly on Earth. Current detectors, such as LIGO (*right*), work by trying to detect tiny changes in length of the four-kilometre-long arms of the detector as a gravitational wave passes.

As we saw with the Crab Nebula, different parts of the electromagnetic spectrum give different information about the source. Gravitational waves have the potential to add to this, opening up a new spectrum that gives information on how the most massive objects change over time.

4. Quakes in the neutron star crust

The cause of these pulsar glitches is unknown. The model we are investigating utilises the fact that a neutron star has a solid crust. In this 'starquake' model, glitches occur when the crust of the star cracks.



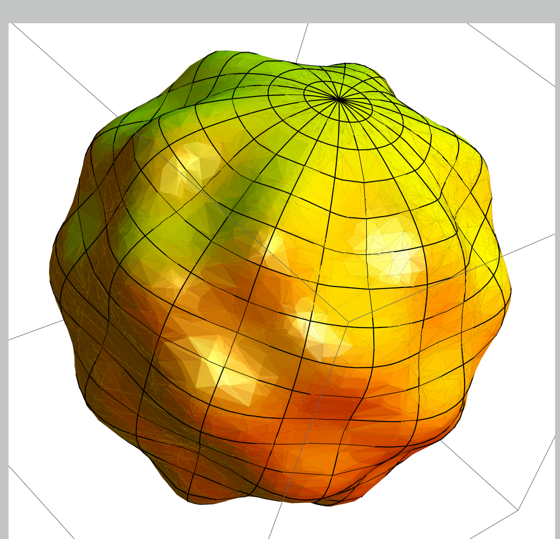
In this model, the star starts out with a relatively unstrained crust. Its fast rotation rate means that it has a slightly elliptical shape.

As it slows down, strain builds up. Eventually the crust reaches a critical level where it can hold no more strain – this is when the starquake occurs.

Immediately after the glitch, the star is out of equilibrium and oscillates for a while. It is these oscillations that promise to be a source of gravitational waves.

The glitch relieves strain from the crust, so that the star's shape becomes closer to spherical. To conserve angular momentum, it must then spin faster. This is the source of the observed speed-up of the radio pulse.

5. Modelling starquakes



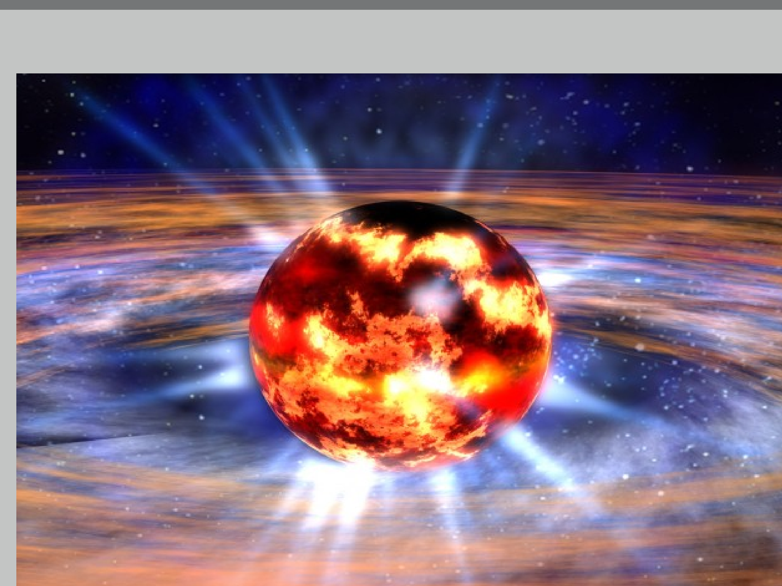
To find the gravitational wave emission from a starquake, we need to know how the star oscillates after the quake. To do this, we have started by creating a toy model: a simplified model that reproduces the essential features of the starquake.

Our main simplifying assumption is that the star is homogeneous and completely solid: this makes calculations much more tractable.

To work out how the star oscillates, we:

- Find the normal modes of the star – the distinctive ways in which it can oscillate. The figure (*above*) shows one such oscillation pattern.
- Find the initial data that describes how the star changes in the glitch.
- Use this initial data to work out which normal modes are excited by the glitch.

6. The future



The toy model has allowed us to get a good idea of how to model a starquake. We will next need to move on to a more realistic model. This will include a fluid core in the star as well as the solid crust. The oscillations of this star will be more complicated, and so the equations must be solved numerically.

This should give us a better understanding of how glitching neutron stars such as the Crab Pulsar can generate gravitational waves.

Image credits:
Glitch figure - adapted from Espinoza *et al.*, 2010; Crab Nebula and starquake images - NASA; LIGO images - LIGO Scientific Collaboration; Pulsar diagram - Wikimedia Commons; Other images - author's own.

lucy.keer@soton.ac.uk