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Gravitational waves from neutron stars

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Abstract. In this presentation, I will outline some of the different ways that neutron stars can generate gravitational waves, discuss recent improvements in modeling the relevant scenarios in the context of improving detector sensitivity, and show how observations are beginning to put interesting “constraints” on our theoretical models.

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1. Context

Neutron stars are cosmic laboratories of exotic and exciting physics. With a mass of more than that of the Sun compressed inside a radius of about 10 kilometers, their density reaches beyond that of nuclear saturation. In essence, our understanding of these extreme circumstances requires physics that cannot be tested in terrestrial laboratories. Instead, we must try to use astrophysical observations to constrain our various theoretical models. We already have a wealth of data from radio, X-ray and gamma-ray observations, providing evidence of an incredibly rich phenomenology. We have learned that neutron stars appear in many different guises, from radio pulsars and magnetars to accreting millisecond pulsars, radio transients and intermittent pulsars. Our models for these systems remain rather basic, despite 40 years of attempts to understand the pulsar emission mechanism, glitches, accreting systems etcetera.

In the next few years we expect “gravitational-wave astronomy” to become reality. This is an exciting prospect, because gravitational-wave (GW) observations should be able to probe several key aspects of neutron star physics. Neutron stars can radiate in a number of ways. Relevant scenarios include; inspiraling binaries, rotating deformed stars, oscillations and instabilities. Modeling these different scenarios is, however, not that easy since our understanding of neutron stars relies on physics that is far from well known. To make progress we must combine supranuclear physics (the elusive equation of state) with magnetohydrodynamics, the crust elasticity, a description of superfluids/superconductors and potentially exotic phases of matter like a deconfined quark-gluon plasma or hyperonic matter. Moreover, in order to be quantitatively accurate, all models have to account for relativistic gravity.

In the last few years the first generation of large-scale interferometric GW detectors (LIGO, GEO600 and VIRGO) have reached design sensitivity in a broad frequency window (Abbott *et al* (2009)). A full years worth of high quality data was taken during the LIGO S5 run. Even though there has not yet been a detection, the experiment has already provided interesting information. At the time of writing, the LIGO detectors are running in an enhanced configuration (with sensitivity improved by about a factor of 2 compared to the S5 run). In the next five year period, they will be upgraded using more advanced technology. Once this upgrade is complete, around 2015, the second generation of ground-based detectors will reach the level of sensitivity where the first detection can be expected. Meanwhile, the discussion of third generation (3G) detectors has begun in earnest with the EU funded Einstein Telescope (ET) design study. The aim for 3G detectors is to improve the broadband sensitivity by (roughly) another order of magnitude.

2. Binary inspiral

The late stage of inspiral of a binary system provides an excellent GW source (Sathyaprakash & Schutz (2009)). As the binary orbit shrinks due to the energy lost to radiation, the GW amplitude rises and the frequency increases as well. This inspiral chirp is advantageous for the observer in many ways. First of all, it is well modeled by post-Newtonian methods and does not depend (much) on the actual physics of the compact objects involved. In fact, much of the signal is adequately described by a point-mass approximation. A key fact that makes binary systems attractive is that the amplitude of the signal is "calibrated" by the two masses (from observations one would expect to be able to infer the individual masses, the spin rates of the objects and the distance to the source). The only uncertainty concerns the event rate for inspirals in a given volume of space. Given this, it is natural to discuss the detectability of these systems in terms of the "horizon" distance d_h at which a given binary signal would be observable with a given detector. Let us assume that detection requires a signal-to-noise ratio of 8, and focus on equal mass neutron star binaries (each star has mass 1.4 $M_\odot$). For such systems, d_h would be 30 Mpc for LIGO S5. In this volume of space one would expect one event every 25-400 yrs. Advanced LIGO should improve this to $d_h = 30$ Mpc, and could see 2-40 events per year, while ET may reach $d_h = 3$ Gpc and could potentially observe thousands of events.

From these estimates we, first of all, see why it would have been surprising if a binary signal had been found in the S5 data. Given even the most optimistic rate estimate from population synthesis models, these events would be rare in the currently observable volume of space. The situation changes considerably with Advanced LIGO. Based on our current understanding, one would expect neutron star binaries to be seen once the detectors reach this level of sensitivity. However, it is also clear that if the most pessimistic rate estimates are correct, then we will not be able to gather a statistically significant sample of signals. Most likely, we will need detectors like ET to study populations.

3G detectors will likely also be required if we want to study the final stages of inspiral, including the actual merger. This is a very interesting phase of the evolution given that the merger will lead to the formation of a hot compact remnant with violent dynamics. It may also trigger a long gamma-ray burst. Most of this dynamics radiates at relatively high frequencies. Tidal disruption occurs above 600 Hz or so and the oscillations of the remnant could lead to a signal at several kHz. However, the merger signal should be rich in information. In particular, the ringdown should tell us directly whether a massive neutron star or a black hole was formed. Roughly, if the inspiral phase is observable with Advanced LIGO then ET should be able to detect the merger. In other words, the development of 3G detectors is essential if we want to study these events.

3. Rotating deformed neutron stars

GWs are generated by asymmetric dynamics. The source could be violent, like a supernova or a binary merger, or slowly evolving, like the binary inspiral. Asymmetries, either in the crust or the magnetic field, are expected to slowly leak rotational energy away from a spinning neutron star. Such sources would be the GW analogue of radio pulsars, radiating at twice the spin frequency. On the one hand, rotating neutron stars will emit low amplitude GWs, but on the other hand, they radiate continuously. Moreover, we have many potential target sources with known frequency and position. This means that observers can carry out a targeted search for known radio and X-ray pulsars.

A key question concerns what level of asymmetry one would expect a neutron star to have. This is a complicated problem, where the answer depends not only on the properties of the star, but also on it's evolutionary history. So far, modeling has mainly focused on establishing what the largest possible neutron star "mountain" would be (Haskell(2008)). Expressing the result in terms of a (quadrupole) ellipticity, theory suggests that $\epsilon < 2 \times 10^{-5} (u_{\rm break}/0.1)$. Recent molecular dynamics simulations suggest that the breaking strain $u_{\rm break} \approx 0.1$, much larger than had been anticipated. In comparison, terrestrial materials have $u_{\rm break} \approx 10^{-4} - 10^{-2}$, so the neutron crust would seem to be super-strong!

Observations of targeted radio pulsars are already providing interesting results. The strongest constraint set by LIGO is $\epsilon < 7 \times 10^{-7}$ for J2124-3358 (based on 1 month of S3/4 data). Thus we know that this relatively fast spinning pulsar is far from maximally deformed. An observational milestone was later reached when S5 data was used to beat Crab pulsar "spin-down limit" by a factor of 4 or so. This result shows that GW emission does not dominate the spin-down of these systems. Although this was already "known" from the pulsar's braking index, it is clear that the observations are beginning to produce astrophysically relevant results.

It is quite easy to estimate how these results are likely to improve in the future since the effective amplitude of a periodic signal increases as the square root of the observation time. In the case of J2124-3358 one would expect analysis of the S5 data (with a factor 2 improved sensitivity, and a full year of data) to improve the constraint to $\epsilon < 10^{-7}$. Advanced LIGO, with an order of magnitude better sensitivity, but still a one year integration, should reach $\epsilon < 10^{-8}$, and ET may push the limit as far as $\epsilon < 10^{-9}$. At this point, the deformation of the star would be constrained to the micron level. One would probably expect a signal to be detected before this level is reached, but we do not know this for sure. The main issue concerns the generation mechanism for deformations. Why should the neutron star be deformed in the first place? This is an urgent problem that needs to be addressed by theorists. As far as evolutionary scenarios are concerned, accreting neutron stars in low-mass X-ray binaries have attracted the most attention (Watts & Krishnan (2009)). This is natural for a number of reasons. First of all, the currently observed spin-distribution in these systems seems consistent with the presence of a mechanism that halts the spin-up due to accretion well before the neutron star reaches the break-up limit. GW emission could provide a balancing torque. The required deformation is certainly smaller than the allowed upper limit, and in an accreting system it would be quite natural for asymmetries to develop. However, accreting systems are very messy, and we do not understand the various torques very well.

4. Oscillations and instabilities

In principle, a promising strategy for constraining neutron star physics involves observing the various modes of oscillation - Andersson (2003). Neutron stars have rich oscillation spectra, with different families of modes more or less directly associated with different core physics. The fundamental f-mode (which should be the most efficient GW emitter) scales with average density, while the pressure p-modes depend on the sound speed and the gravity g-modes are sensitive to thermal/composition gradients. In a rotating star, the inertial r-modes are restored by the Coriolis force. The r-modes are particularly interesting because they may be driven unstable by the emission of GWs.

The r-mode instability window depends on a balance between GW driving and various dissipation mechanisms. This provides a sensitive probe of the core physics. Because of

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this, the r-mode has been studied in a variety of contexts in the last decade. We now know that important issues concern the damping due to the vortex mediated mutual friction in a superfluid, the boundary layer at the crust-core interface and exotic bulk viscosity due to the presence of hyperons or deconfined quarks in the deep neutron star core. These problems are all very challenging. In addition, we need to be model the GW signal from an unstable r-mode. This is also difficult because, even though the r-mode growth phase is adequately described by linear theory, nonlinear effects soon become important. Detailed studies show that the instability saturates at a low amplitude due to coupling to other inertial modes. The subsequent evolution is very complex.

To model a truly realistic oscillating neutron star may be difficult, but the potential reward is considerable. This is clear from recent results for the quasiperiodic oscillations seen in the tails of magnetar flares. These oscillations have been interpreted as torsional oscillations of the neutron star crust. If this is correct, then we are already doing neutron star asteroseismology! The current models are perhaps not that precise, but they should motivate us to improve our understanding of the key physics (like the interior magnetic field and the dynamical coupling between the crust and the core). The magnetar events may also generate GWs. Having said that, LIGO found no signal from the 27/12 2004 event in SGR 1806-20. This is perhaps not surprising because pure crust oscillations do not generate strong GWs (due to the low density involved). The situation would change if the dense core were involved in the oscillation, but it is not yet clear to what extent this is the case.

5. Summary and future challenges

GW astronomy promises to provide insights into the "dark side" of the Universe. Because of their high density, neutron stars are ideal GW sources and we hope to be able to probe the extreme physics of their interiors. The potential for this is clear, in particular with 3G detectors like the ET. However, in order to detect the signals and extract as much information as possible, we need to improve our theoretical models considerably.

For binary inspirals, we need to work out when finite size effects begin to affect the evolution. We need to consider tidal resonances and compressibility in detail and ask to what extent they affect the late stages of inspiral. For hot young remnants, resulting from binary mergers or core collapse, we need to refine our large scale numerical simulations. The simulations must use "realistic" equations of state, and consider composition, heat/neutrino cooling and magnetic fields with as few "cheats" as possible. In parallel, we need improve our current understanding of neutron star oscillations and instabilities. This effort should aim at accounting for as much of the interior physics as possible. Finally, we need a clearer phenomenological understanding of pulsar glitches, accreting neutron stars, magnetar flares etcetera. These are ambitious targets, but there is no reason why we should not make good progress in the next few years. Eventually, future observations (gravitational and electromagnetic) will undoubtedly help us understand many of the aspects of neutron star physics that seem mysterious to us today.

References

Abbott, B. P., *et al* 2009, *Rep. Prog. Phys.* 72, 076901
Andersson, N. 2003, *Class. Quantum Grav.* 20, R105
Haskell, B. 2008, *Class. Quantum Grav.* 25, 114049
Sathyaprakash, B. S. & Schutz, B. F. 2009, *Liv. Rev. Relativity*, vol. 12, no. 2
Watts, A. L. & Krishnan, B. 2009 *Adv. Sp. Res.* 43, 1049