Neutron Stars as Gravitational Wave Sources

Leonardo Gualtieri
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Leonardo Gualtieri                     Rencontres de Moriond                   La Thuile, March 2011
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=> NS are promising sources of Gravitational Waves (GW)!

Leonardo Gualtieri         Rencontres de Moriond         La Thuile, March 2011
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We probably know how it is organized matter in the crust of a NS, maybe also in the outer core, but we do not know the behaviour of matter \textit{in the inner core of a NS} where it reaches supranuclear densities which cannot be reproduced in the lab.
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Hadron interactions play a crucial role (if they are neglected and neutron Fermi pressure only is considered, one finds $M \leq 0.7M_{\text{sun}}$, but we observe $M \sim (1.2-2)M_{\text{sun}}$)

Our lack of knowledge on the NS Equation of State (EOS) (we do not even know the particle content in the core: Hadrons? Hyperons? Meson condensates? Deconfined quark matter [i.e. Strange Stars as in Witten '84]?) reflects our ignorance on the non-perturbative regime of QCD.
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If *GW* teach us how *NS* are and behave, for instance which is their radius $R$
(a “clean” observation of $R$ in the EM spectrum is very difficult)
we would learn also something about the nature of hadronic interactions.
Figure 3: Neutron star (NS) mass-radius diagram. The plot shows neutron-rotating mass versus physical radius for several typical NS equations of state (EOS) [25]. The horizontal bands show the observational constraints from our J1614−2230 mass measurement of $1.97 \pm 0.04 \, M_{\odot}$, similar measurements for two other millisecond pulsars [3, 26], and the range of observed masses for double NS binaries [2]. Any EOS line that does not intersect the J1614−2230 band is ruled out by this measurement. In particular, most EOS curves involving exotic matter, such as kaon condensates or hyperons, tend to predict maximum NS masses well below $2.0 \, M_{\odot}$, and are therefore ruled out.

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(Demorest et al., Nature ’10)
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In this talk I will discuss some GW NS processes, looking both:

i) whether detectable GW can be produced;
ii) whether GW detection could tell something about the NS EOS

(Demorest et al., Nature ’10)
NS as GW sources: Gravitational Wave Asteroseismology


When a NS is perturbed by some external or internal event, it can be set into non-radial, damped oscillations, the quasi-normal modes (QNM) \( \Rightarrow \) GW emission.

The detection of these signals will allow to measure the oscillation frequencies and damping times of the QNM, which carry information on the structure and EOS of the star.
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The QNM are classified depending to the main restoring force:

- g-modes: buoyancy force, not efficient in radiating GW (few hundreds of Hz)
- p-modes: pressure (few thousands of Hz)
- f-mode: the fundamental mode, intermediate between g and p (1-2 kHz) it is the most efficient in radiating GW
- w-modes: pure space-time modes (many kHz)

If we include more physics, there are also:

- r-modes: Coriolis force (for rotating stars only)
- magnetic modes
- elastic modes (in the crust)
**NS as GW sources:** Gravitational Wave Asteroseismology

QNM of cold, old Neutron Stars

A GW-detection from a pulsating star could allow us:

- to infer the value of the NS radius $R$, strongly constraining the EOS
- to discriminate between different possible EOS
- to establish whether the emitting source is a NS or a quark star,
- if it is a quark star, to constrain the quark star EOS.

(O. Benhar, V. Ferrari, L.G., PRD ‘04; O. Benhar, V. Ferrari, L.G., S. Marassi, GRG 39, 1323, ‘07)

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However, there is much more than the f-mode of non-rotating cold stars. In recent years, a lot of effort has been devoted in many groups (Tubingen, Southampton, Rome, Tessaloniki, etc.) to model different kinds of NS oscillations including more and more physics in the game:
However, there is much more than the f-mode of non-rotating cold stars. In recent years, a lot of effort has been devoted in many groups (Tubingen, Southampton, Rome, Tessaloniki, etc.) to model different kinds of NS oscillations including more and more physics in the game:

**QNM of rotating NS**
They are extremely important, because these modes can become unstable, with a large gravitational emission.

**QNM of magnetized NS**
Especially oscillations of the crust, eventually coupled with the core. Results can be compared with observational data from giant flares in magnetars.

**QNM of superfluid NS**
NS (if not too young) are indeed superfluid, and this seems to affect significantly the QNM.
QNM of hot, young Neutron Stars
In a proto-neutron star (PNS) the effects of $s, T, Y_i$ are important.
QNM of hot, young Neutron Stars

In a proto-neutron star (PNS) the effects of $s, T, Y_i$ are important.

(V. Ferrari, G. Miniutti, J.A. Pons, MNRAS ‘03)

The EOS is derived with the mean field approximation, the evolution of thermodynamical quantities is computed solving Boltzmann’s eq.
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The EOS is derived with the mean field approximation, the evolution of thermodynamical quantities is computed solving Boltzmann’s eq.

(F. Burgio, V. Ferrari, L.G., H.-J. Schultze PRD ’11, to appear)

EOS derived with nuclear many-body theory; evolution of thermodynamical quantities guessed from previous simulations, i.e.
NS as GW sources: Gravitational Wave Asteroseismology

Some indications from these studies:
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**QNM of cold, old Neutron Stars**

- It is most likely to detect f-mode, more efficient in radiating GW
- Typical f-mode frequency about 1 kHz and above.

  It would be very important to have detectors sensible at high frequencies!

This should be taken into account in the design of II\textsuperscript{nd} and III\textsuperscript{rd} generation detectors!
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QNM of hot, young Neutron Stars

The frequencies are smaller => better for LIGO/Virgo detection!

The g-mode frequency is related to the entropy gradient, thus detecting this mode we would learn about the thermodynamics of early PNS

g-modes are similar to f-mode, both in frequency (few hundreds Hz) and damping time (some seconds), because the eigenfunctions are similar.
So, in PNSs not only the f-mode, but also the g-mode is efficient in radiating GW
NS as GW sources:  **Gravitational Waves from NS in binaries**

I’ll not speak about the detectability of GW from NS in binary systems, since other talks discuss this topic. I will instead mention a couple of examples showing how GW from NS in binaries can give us information about the NS Equation of State.
**NS as GW sources:** Gravitational Waves from NS in binaries

**Tidal disruption of Neutron Stars**
(M. Vallisneri, PRL ’00; V. Ferrari, L.G., F. Pannarale CQG ’09, PRD ’10)

The coalescence of binary compact objects (BH-BH, BH-NS, NS-NS) is a very promising source of gravitational waves.
(Advanced LIGO/Virgo should detect ~1 BH-NS coalescence per year).

If the NS is disrupted by the BH tidal field before entering into the BH and forms an accretion disc, the GW signal exhibits a cutoff frequency $\nu_{GW\text{tide}}$, a distinctive feature of the waveform which can give us information on the NS EOS.
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If we know, from the detected signal, the BH mass and angular momentum and the cutoff frequency $V_{\text{GW tide}}$, we can determine the NS radius with an error of a few percent, and discriminate between possible alternative EOS.
NS as GW sources: Gravitational Waves from NS in binaries

Tidal deformation of Neutron Stars in binaries

In the inspiral phase of a NS-NS binary, the waveform is affected by tidal deformation of the NS, which depends on the EOS.

It is possible to extract from the GW waveform the tidal deformability $\lambda$ of the NS that gives information on the EOS:

(T. Hinderer, B.D. Lackey, R.N. Lang, J.S. Read PRD ’10)
NS as GW sources: Deformed Neutron Stars

If a NS has an ellipticity $\varepsilon$ and rotates about an axis misaligned by $\alpha$ with the symmetry axis, it emits GW with amplitude:

$$h_0 \simeq \frac{4G}{rc^4}(2\pi\nu)^2 I |\varepsilon| \sin \alpha.$$  \hspace{1cm} (11)

Similar expressions apply for more complicate shapes (triaxial stars, “mountains”, etc.)
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Even with **present** detectors, GW can explore a region of the parameter space for NS deformations inaccessible otherwise!


![Graph showing moment of inertia vs. ellipticity](image)

However, we do not know how large is the NS deformation $\varepsilon$. We can only try to model different possible deformation mechanisms, like accretion and magnetic fields.
NS as GW sources: Deformed Neutron Stars

Accretion
NS as GW sources: Deformed Neutron Stars

Accretion

Rapidly accreting NS all rotate with similar frequencies $\nu \sim 300$ Hz. As suggested by Bildsten (ApJ '98), this could be due to GW emission. Indeed, accreted matter induce quadrupole deformation which yields GW emission. In this scenario, GW emission would balance the spin-up induced by accretion. If there is no other spin-down mechanism (i.e. EM spin-down negligible), this GW emission may be detectable from the Advanced LIGO/Virgo detectors.
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However, the nature of the NS crust limits the possible deformations: if $\varepsilon > \varepsilon_{\text{max}} \sim 10^{-7} - 10^{-6}$ (but if exotic matter, up to $10^{-3}$), the crust breaks (Ushomirsky et al. MNRAS ‘00; Haskell et al. MNRAS ’06, PRL ‘07; Horowitz et al. PRL ‘09).
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Open circles: spindown upper limits
Close circles: taking into account $\varepsilon > \varepsilon_{\text{max}}$
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(Andersson et al. GRG ’11)

Open circles: spindown upper limits
Close circles: taking into account $\varepsilon > \varepsilon_{\text{max}}$
Actually, detection is even more difficult, due to our ignorance of the astrophysical features of the NS (Watts et al. Adv.S.Res. ’09)
NS as GW sources: Deformed Neutron Stars

Magnetic field
NS as GW sources: **Deformed Neutron Stars**

**Magnetic field**

NS can have extremely large magnetic fields ("magnetars"), up to $10^{15}$ on the surface, and even larger in the interior.

These magnetic fields can produce large deformations => GW emission

$$\epsilon_Q \simeq k \left[ \frac{B_{pole}(G)}{10^{16}} \right]^2 \times 10^{-4}$$ (k ~ 4-9 depending on the EOS)

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\]

Some facts about magnetars:

- Their magnetic field make them tremendously EM-active: giant flares can reach the peak luminosity of $10^{47}$ erg/s ('04 flare of 1806-20)

- All observed magnetars have very low rotation rates (periods of seconds), since the large magnetic field make dipole spin-down very efficient: $P \dot{P} \sim B^2$

- So, their GW emission is not in the LIGO/Virgo bandwidth

- It is believed that a fraction of newly born NS are magnetars, rapidly rotating, thus possible LIGO/Virgo sources
**NS as GW sources: Deformed Neutron Stars**

If a NS has been deformed by the magnetic field at birth, its ellipticity could be larger than $\varepsilon_{\text{max}}$ since the NS was then hot and without crust: if when the crust freezes the star is already deformed, the NS can in principle maintain a large deformation without crust breaking.

The problem with this scenario is that if the star is so deformed, and so strongly magnetized, it also has a strong dipole moment which spins it down, outside the LIGO/Virgo bandwidth. Therefore, either there is some external process which keeps the star rapidly rotating, or it can only emit at birth, and this would imply a low event rate (1-few per century, like SN).
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A galactic NS with \( B=10^{15} \text{G} \), \( M=1.4M_\odot \), \( \alpha=3^\circ \) would emit in the detector band for few months (due to electromagnetic spindown), with:

\[
\begin{align*}
\text{1e-28} & \quad \text{1e-27} & \quad \text{1e-26} & \quad \text{1e-25} & \quad \text{1e-24} \\
\text{10} & \quad \text{100} & \quad \text{1000} \\
\text{ET} & \quad \text{AdvLIGO} & \quad \text{AdvVirGO} & \quad \text{GNH3} & \quad \text{APR2}
\end{align*}
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Marginally detected by Advanced LIGO/Virgo, well detected by ET.

(L.G., R. Ciolfi, V. Ferrari, CQG ’11 I, to appear)
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But if there is no spin-up mechanism, such process has a low event rate.