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# Gravitational waves from neutron stars and asteroseismology

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Neutron stars are born in the supernova explosion of massive stars. Neutron stars rotate as stably as atomic clocks and possess densities exceeding that of atomic nuclei and magnetic fields millions to billions of times stronger than those created in laboratories on Earth. The physical properties of neutron stars are determined by many areas of fundamental physics, and detection of gravitational waves can provide invaluable insights into our understanding of these areas. Here we describe some of the physics and astrophysics of neutron stars and how traditional electromagnetic wave observations provide clues to the sorts of gravitational waves we expect from these stars. We pay particular attention to neutron star fluid oscillations, examining their impact on electromagnetic and gravitational wave observations when these stars are in a wide binary or isolated system, then during binary inspiral right before merger, and finally at times soon after merger.

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## 1. Introduction

When a massive star runs out of fuel to power thermonuclear reactions in its core, it undergoes a supernova, and the core forms either a neutron star or a black hole. In the case of the former, the resulting neutron star has a mass just above that of the Sun but is only about 25 km in diameter. The compactness and gravity of neutron stars makes them, like their black hole relatives, potentially strong sources of gravitational waves. But because neutron stars have a hard surface and are composed of normal particles, these stars are unique tools for advancing our knowledge of many areas of physics, including nuclear, particle, and plasma physics and condensed matter and low temperature physics. For example, some nuclear theories predict the presence of exotic particles, such as hyperons and deconfined quarks, in the star's core at densities above nuclear saturation, i.e., at baryon densities $> 0.16\ \mathrm{fm}^{-3}$ (see, e.g., [1,2], for review). Theory and observations also indicate the neutron star core may contain a neutron superfluid and proton superconductor [3–5].

Rotating neutron stars, also known as pulsars, were discovered by radio observations 50 years ago [6]. Since then, more than 2600 pulsars have been found and tracked over time, allowing measurements of each star's spin period $P$ and spin period time derivative $\dot{P}$. Figure 1 shows $P$ and $\dot{P}$ values of each pulsar taken from the ATNF Pulsar Catalogue [11].

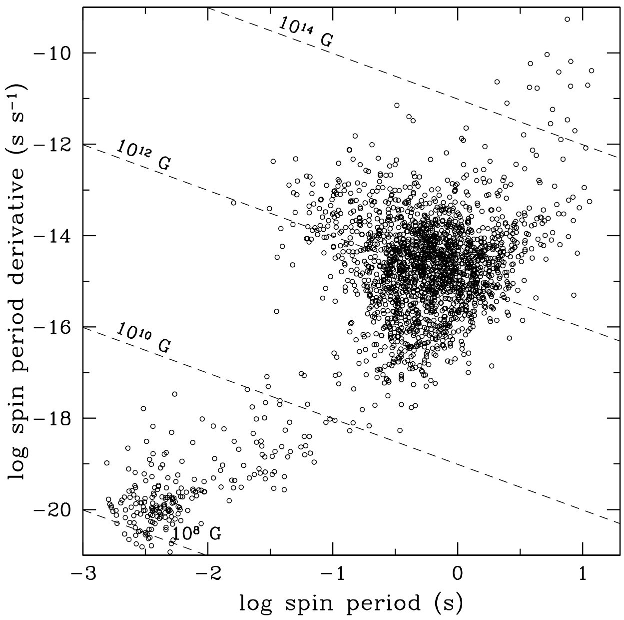


**Figure 1.** Pulsar spin period $P$ versus spin period time derivative $\dot{P}$. Points denote pulsars whose values are taken from the ATNF Pulsar Catalogue [11]. Dashed lines indicate magnetic field $B$ based on the relation $B = 3.2 \times 10^{19}\ \mathrm{G}(P\dot{P})^{1/2}$ (see text).

The model used to explain a pulsar's detectable electromagnetic radiation is that the neutron star is a rotating magnetic dipole, such that its energy loss or luminosity is

$$L_{\mathrm{mag}} = -\frac{B^2 R^6 \Omega_{\mathrm{s}}^4 \sin^2\theta}{6c^3}, \tag{1.1}$$

where $B$, $R$, and $\Omega_{\mathrm{s}}(= 2\pi/P)$ are neutron star magnetic field strength, radius, and angular spin frequency, respectively, and $\theta$ is angle between rotation and magnetic axes [7,8] (see also [9,10]). Electromagnetic energy is emitted in a beam along the open magnetic field lines around the magnetic poles, producing a "lighthouse" effect of pulses of radiation once or twice a rotation period. This radiation comes at the expense of the pulsar's rotational energy. By equating $L_{\rm mag}$ to rotational energy loss [$= I\Omega_{\rm s}\dot{\Omega}_{\rm s}$; see equation (4.2)], the magnetic field $B$ of each pulsar can be deduced from its measured $P$ and $\dot{P}$, i.e., $B = 3.2\times 10^{19}\,{\rm G}(P\dot{P})^{1/2}$, where units of $P$ and $\dot{P}$ are s and s s$^{-1}$, respectively. The result is that most pulsars have $B\sim 10^{11}-10^{13}$ G, as is evident from Figure 1. There are also many "millisecond pulsars" with short spin periods $P<10$ ms and $B\sim 10^{8}-10^{9}$ G and a few "magnetars" with long spin periods $P\gtrsim 1$ s and $B\sim 10^{13}-10^{15}$ G.

With detection of gravitational waves from the inspiral and coalescence of two neutron stars [12], we now have the capability to obtain new observables that can be used to infer properties of neutron stars. For example, the gravitational wave signal from GW170817 (see Figure 2) allows measurement of the mass of each neutron star and the amount of tidal distortion each star causes on the other.

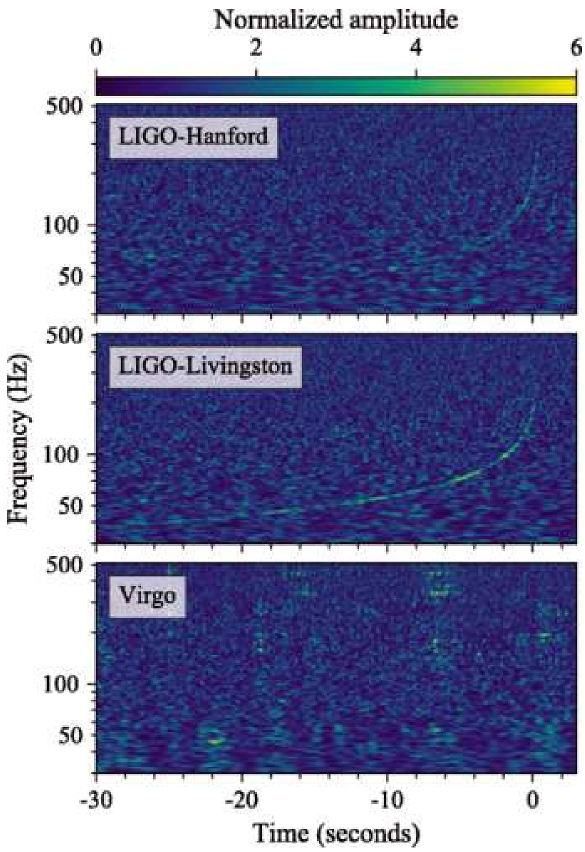


**Figure 2.** From Abbott et al. 2017 [12]: Gravitational wave frequency as a function of time as measured by the detectors at LIGO-Hanford (top), LIGO-Livingston (middle), and Virgo (bottom). The color scale indicates the amplitude of the gravitational wave signal from the source GW170817.

In this work, we evaluate some effects of fluid oscillations of neutron stars on electromagnetic and gravitational wave observations and how one could use these observations to better understand the physics and astrophysics of neutron stars. In Section 2, we briefly describe neutron star fluid oscillations, such as the r-mode, and some of the physics that govern them. In Section 3, we consider tidal excitation of fluid oscillations and the effect this can have on gravitational wave signals during binary inspiral. Finally, in Section 4, we examine the possible impact gravitational wave emission due to r-modes has on electromagnetic observations of a neutron star remnant after a binary system merges.

## 2. Neutron star seismology and r-mode oscillations

One technique that has been extremely useful for understanding properties of the Sun and other types of stars, especially their deep stellar interior, is asteroseismology. This involves studying the various fluid oscillations (or modes) seen in stars, since different stellar properties determine the behavior of these oscillation modes. For neutron stars, some of the relevant oscillation modes are the f-mode (fundamental mode), p-modes (pressure or acoustic waves), g-modes (gravity modes due to chemical composition and temperature gradients), and r-modes (Rossby waves due to Coriolis effect) (see, e.g., [13]). The frequency of the f-mode is about 1 kHz, while p-modes have frequencies above that of the f-mode. G-mode frequencies in neutron stars are $\lesssim$ a few $\times$ 100 Hz, and r-modes frequencies are on order of $\nu_s$ $(= \Omega_s/2\pi)$. Thus g-modes and r-modes are particularly interesting given LIGO's optimal gravitational wave frequency range of a few tens of Hz to several hundreds of Hz. In the present work, we will focus attention on r-modes.

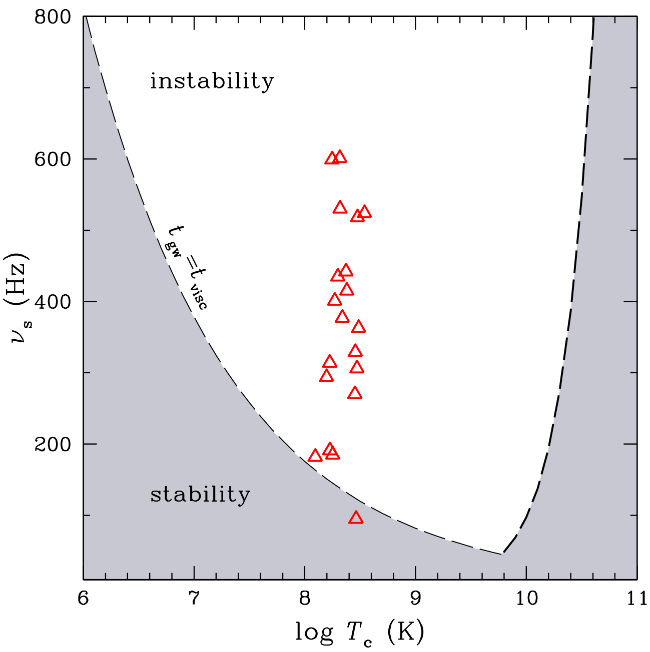


**Figure 3.** R-mode instability window. Neutron star spin frequency $\nu_s$ versus core temperature $T$. The dashed line denotes the boundary set by $t_{gw} = t_{visc}$, with the shaded "stability" region set by $t_{gw} > t_{visc}$ and r-mode is damped by viscosity and unshaded "instability" region set by $t_{gw} < t_{visc}$ and r-mode grows by emission of gravitational waves. Triangles denote neutron stars in low-mass X-ray binary systems whose $\nu_s$ are measured and $T$ are inferred (see [20], for details).

R-modes in neutron stars generated great interest over the past 20 years because they were shown to be generically unstable to emission of gravitational waves [14,15] via the Chandrasekhar-Friedman-Schutz instability [16,17]. For this instability to occur, an oscillation mode propagates in the opposite (retrograde) direction as the star's rotation in the rotating frame but propagates in the same (prograde) direction as the rotation in the frame of a distant observer. The varying shape of the star due to the oscillation and rotation generates gravitational waves, and as gravitational waves are emitted, angular momentum is carried away which causes the oscillation mode to grow. Viscosity in the star limits mode growth, such that an oscillation mode is prevented from growing if the timescale for viscous damping is shorter than the timescale for gravitational wave emission, i.e., $t_{gw} > t_{visc}$, while a mode will grow and be a source of gravitational waves when $t_{gw} < t_{visc}$. This is illustrated for the r-mode in Figure 3, which shows the "r-mode instability window" based on two of the primary factors (neutron star spin frequency

$\nu_s = 1/P$ and core temperature $T_c$) that determine $t_{gw}$ and $t_{visc}$ [18,19], as well as values for neutron stars in systems where $\nu_s$ and $T_c$ can be determined (see [20], and references therein). By studying r-modes, we hope to investigate processes and properties which govern $t_{visc}$, such as neutrino emission, crust elasticity, superfluidity, and hyperonic and quark matter [18,20,24].

Figure 3 shows many neutron stars should be unstable to r-mode growth and thus are potentially strong sources of gravitational waves. This in part motivated prior searches by LIGO for r-modes in pulsars [21–23]. However it is important to keep in mind that our theoretical understanding of the physics that determines $t_{visc}$ indicate the "instability window" should be much smaller [20,24] and that we expect few sources to lie within the window compared to the number of sources outside the window [25,26].

# 3. Oscillation mode excitation during binary coalescence

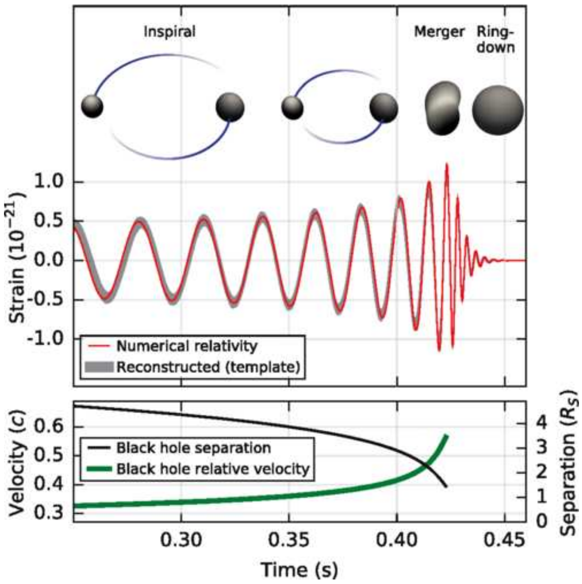


**Figure 4.** From Abbott et al. 2016 [27]: Schematic of binary inspiral and merger of two compact stars (top), gravitational wave strain (middle), and velocity and binary separation (bottom) as a function of time for GW150914.

The aforementioned discussion of oscillation modes is in the context of an isolated neutron star or a neutron star which has a companion star with an orbital evolution timescale that is many years. On the other hand, gravitational wave sources such as GW150914 [27] and GW170817 [12] are binary systems whose orbital evolution and coalescence takes place with a duration on the order of seconds. Asteroseismology and r-modes can play a role in these latter systems as well, and one can learn about properties of neutron stars and fundamental physics via the impact of oscillation modes on gravitational wave signals from binary inspiral sources such as GW170817. This can be understood using the illustration of the inspiral and coalescence of two compact stars shown in Figure 4, courtesy of [27]. Consider one or both compact stars to be a neutron star. As the two stars inspiral and move closer and closer together, the orbital frequency $\Omega_{orb}$ increases, e.g., from a few tens of Hz to more than a kHz (see, e.g., Figure 2). This frequency range contains the characteristic frequencies of various neutron star oscillation modes described in Section 2. Coupling and resonance can occur between a mode frequency $\omega_\alpha$ and the orbital frequency (e.g., $\omega_\alpha = 2\Omega_{orb}$), such that energy is transferred into (or out of) the mode at the cost (or benefit) of the orbit. In other words, energy is drawn from the orbit and is used to excite an oscillation mode. Since the orbit has lost energy, the orbit will shrink faster. This would manifest as a change in the gravitational waveform (see Figure 4) due to a decrease in the number of orbits the binary system undergoes before coalescence and a change in the gravitational wave frequency evolution [28–32]. In the extreme case, it is possible enough energy is pumped into the neutron star that its crust will fracture or shatter, producing an electromagnetic flare before merger of the compact stars [33,34].

The identification of a particular mode that is excited during a segment of the inspiral would have important implications for our understanding of neutron stars. For example, the frequency of a resonant r-mode depends on the neutron star's mass and radius due to General Relativistic corrections [35]. By combining a measured r-mode frequency with the extracted mass and spin of the neutron star obtained from the gravitational wave signal at merger, it may be possible to measure the radius of the neutron star and enable strong constraints on the nuclear equation of state. However tidal coupling between the orbit and most oscillation modes is thought to be weak [29–32,36].

## 4. Rapidly rotating, magnetic neutron star after merger/collapse

The association of the binary neutron star merger GW170817 with the (short) gamma-ray burst GRB170817A [37–39] allows us to confidently utilize theoretical ideas and models developed regarding the origin of gamma-ray bursts. In particular, one model for (short type of) gamma-ray bursts entails the formation of a rapidly rotating, strongly magnetic neutron star remnant from the merger of two neutron stars [40–42]. This "millisecond magnetar" model is invoked in order to provide an additional source of energy over an extended period of time after merger to explain the observed evolution of luminosity seen in some gamma-ray bursts (see, e.g., [43,44]).

The millisecond magnetar model is relatively simple and is based on coupling between the equation for the rate of change of energy (see, e.g., [45])

$$\frac{\partial E}{\partial t} = -p\frac{\partial V}{\partial t} - L_{\rm rad} + L_{\rm mag}, \tag{4.1}$$

where $E$ is thermal energy, $p$ is pressure, $V$ is volume, $-L_{\rm rad}$ is energy loss via photons, and $+L_{\rm mag}$ is energy supplied by the rotating neutron star [see equation (1.1)], and the equation for spin frequency evolution

$$I\Omega_{\rm s}\dot{\Omega}_{\rm s} = -L_{\rm mag} - L_{\rm gw}, \tag{4.2}$$

where $-L_{\rm gw}$ is energy loss via gravitational wave emission. First, let us ignore gravitational wave emission, i.e., $L_{\rm gw} = 0$. An example of the solution of equations (4.1) and (4.2) is shown in Figure 5; note that the specific results shown here are relevant for supernovae but results for gamma-ray bursts are qualitatively similar (see [46], for details).

Now consider the role of gravitational wave emission, i.e., $L_{\rm gw} \neq 0$ [46–49]. In particular, let us consider if gravitational wave emission is due to the r-mode instability [46], as described in Section 2. Then $L_{\rm gw} \propto \alpha^2\Omega_{\rm s}^8$, where $\alpha$ is the dimensionless amplitude of the r-mode [18], and is effective at just the fast spin rates needed for the millisecond magnetar model. From Figure 5, we see that a large amplitude r-mode causes the neutron star spin period $P$ to increase (or spin rate $\Omega_{\rm s}$ to decrease) more rapidly and this robs the amount of energy that can be supplied [since $L_{\rm mag} \propto \Omega_{\rm s}^4$; see equation (1.1)] to power electromagnetic radiation $L_{\rm rad}$. However, as discussed in [46], the r-mode amplitude $\alpha$ needed to noticeably alter the luminosity predicted by the millisecond magnetar model and impact comparisons to observations of gamma-ray bursts (and supernovae) is substantial and unlikely. Incidentally, the same is true for gravitational waves from deformations of a neutron star, where $L_{\rm gw} \propto \varepsilon^2\Omega_{\rm s}^6$ and $\varepsilon$ is the dimensionless deformation size; the deformation must be large and probably unrealistic to have an effect on analyses of gamma-ray burst observations.

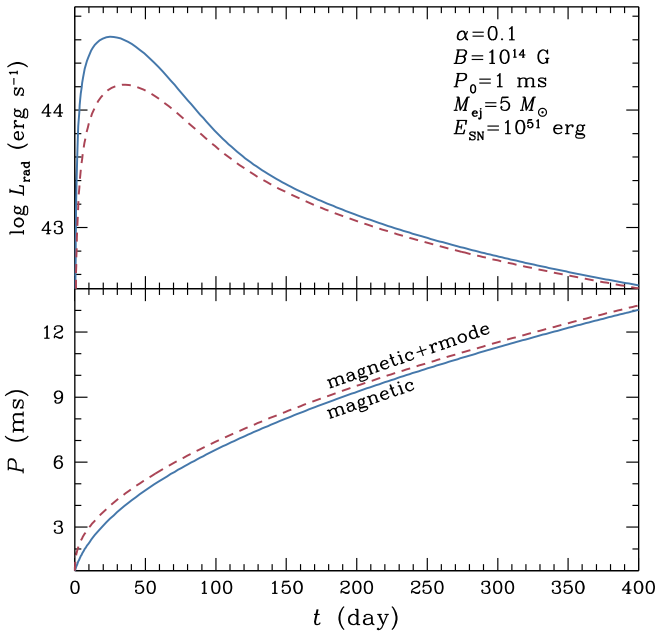


**Figure 5.** Luminosity (top) and neutron star spin period $P$ (bottom) as a function of time. Solid lines are for a model with ejecta mass $M_{\rm ej}=5\,M_{\rm Sun}$ and supernova energy $E_{\rm SN}=10^{51}$ erg and only includes magnetic dipole energy loss $L_{\rm mag}$ with magnetic field $B=10^{14}$ G and initial spin period $P_0=1$ ms. Dashed lines are for a model which includes magnetic dipole $L_{\rm mag}$ and gravitational energy loss $L_{\rm gw}$, with r-mode amplitude $\alpha=0.1$.

## 5. Conclusion

Over the last 50 years since their discovery [6], neutron stars have proven to be unique and vital tools for learning about the Universe. For example, the agreement between the measured rate of orbital decay in a binary neutron star system and the prediction of General Relativity provided the first confirmation of gravitational waves [50,51]. Another example is the detection of multiple planets orbiting a neutron star, which were the first planets discovered beyond our solar system [52]. With the recent detection of gravitational and electromagnetic waves from a binary neutron star inspiral [53], a new era of astronomy begins, and a new window into understanding the Universe opens. The future will continue to be bright for neutron star studies in this era of multi-messenger astronomy, not only because of GW170817, but because of the recently launched X-ray telescope, *Neutron Star Interior Composition Explorer* (*NICER*) [54]. *NICER*'s measurements of pulsars could be combined with searches by LIGO/Virgo to not only provide constraints on r-mode oscillations [55] but also to reveal a new class of gravitational wave sources.

Competing Interests. The author declares that he has no competing interests.

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