Neutron Star Dynamics and Gravitational Waves

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Abstract. As several large scale interferometers are beginning to take data at sensitivities where astrophysical sources are predicted, the direct detection of gravitational waves may well be imminent. This would open the gravitational-wave window to our Universe and should lead to a much improved understanding of the most violent processes imaginable; the formation of black holes and neutron stars following core collapse supernovae and the merger of compact objects at the end of binary inspiral. Among the best candidate sources for gravitational waves are the oscillations, but mainly the rotational instabilities of neutron stars which can emit quite strong gravitational wave signals via which one may reveal the details of their structure. Magnetars also are neutron stars with ultra strong magnetic field whose periodic flaring activity is associated with starquakes. They are also a potential source of gravitational waves while even the quasi-periodic oscillations (QPOs) observed in the electromagnetic spectrum can reveal the details of their structure.

1. Introduction

Gravitational waves are ripples of spacetime generated as masses are accelerated. It is one of the central predictions of Einstein’s general theory of relativity but despite decades of effort, these ripples in spacetime have still not been observed directly. Yet we have strong indirect evidence for their existence from the excellent agreement between the observed inspiral rate of the binary pulsar PSR1913+16 and the theoretical prediction (better than 1% in the phase evolution). This provides confidence in the theory and suggests that “gravitational-wave astronomy” should be viewed as a serious proposition. This new window into the universe will complement our view of the cosmos and will help us unveil the fabric of spacetime around black-holes, observe directly the formation of black holes or the merging of binary systems consisting of black holes or neutron stars, search for rapidly spinning neutron stars, dig deep into the very early moments of the origin of the universe and look at the very center of the galaxies where supermassive black holes weighing millions of solar masses are hidden. Secondly, detecting gravitational waves is important for our understanding of the fundamental laws of physics; the proof that gravitational waves exist will verify a fundamental 90-year-old prediction of general relativity. Also, by comparing the arrival times of light and gravitational waves from e.g. supernovae, Einstein’s prediction that light and gravitational waves travel at the same speed could be checked. Finally, we could verify that they have the polarization predicted by general relativity. For detailed reviews on gravitational wave astronomy one can refer to [1, 2]

Neutron stars are cosmic laboratories for extreme physics. With densities reaching values beyond nuclear saturation they represent the densest states of cosmic matter. These extreme densities cannot be achieved in terrestrial laboratories and thus the astrophysical observations remain as the only tool of testing our theoretical models. During the last 50 years we managed via radio, X-ray and gamma ray observations to improve our understanding of the features
observed on these extreme objects. They are observed as radio pulsars, as magnetars or as millisecond pulsars, isolated or in binary systems. Still our models remain quite basic, despite of the efforts into modeling the violent dynamics of supernovae and gamma-ray bursts, or the radio pulsar emission mechanism, the glitches etcetera.

During their evolution, neutron stars may undergo oscillations which can become unstable under certain conditions. Newly born neutron stars are expected to oscillate wildly during their creation shortly after the supernovae collapse [3, 4]. They are also expected to oscillate if they are members of binary systems and there is tidal interaction [5, 6] or mass and angular momentum transfer from a companion star and also when they undergo phase transitions [7, 8], which might be responsible for the observed glitches in pulsars. Rotation strongly affects these oscillations and perturbed stars can become unstable if they rotate faster than some critical velocities. During these oscillatory phases of their lives, compact stars emit copious amounts of gravitational waves which together with viscosity tend to suppress the oscillations. The oscillations are divided into different families according to the restoring force [9, 10]. If pressure is the main restoring force, then these modes are called (pressure) \( p \)-modes, buoyancy is the restoring force of another class of oscillation modes, the \( g \)-modes while Coriolis force is the restoring force for the \( \text{inertial modes} \). Spacetime induces another family of oscillations which couple only weakly to the fluid, these are the so-called \( w \)-modes [11]. There are more families of modes if one assumes the presence of crust [12, 13, 9, 14] or magnetic fields [15]. For a complete description of perturbation theory for relativistic stars one may refer to [10, 16, 17].

During the last two decades, the study of neutron star dynamics has become even more important due to the relations of the oscillations and instabilities to the emission of gravitational waves and the possibility of getting information about the stellar parameters (mass, radius, equation of state) by the proper analysis of the oscillation spectrum [18, 19, 20, 21, 22, 23]. Still, all these studies were mainly dealing with non-rotating stars, because the combination of rotation and general relativity made both the analytic and numerical studies extremely involved. This led to certain approximations in studying rotating stars in GR. The most obvious of them include the so called “slow-rotation” and the “Cowling” approximation. In the slow rotation approximation, one expands the perturbation equations in terms of a small parameter \( \varepsilon = \Omega/\Omega_K \), where \( \Omega \) is the angular velocity of the star and \( \Omega_K \) stands for the “Kepler angular velocity” which is the maximum velocity that can be attained before the star splits apart due to centrifugal forces. In the Cowling approximation, one typically neglects the perturbations of the Newtonian potential or the spacetime in the case of GR. This is a quite good approximation, both qualitatively and quantitatively, for high order \( p \)-modes, for the \( g \)-modes and the inertial modes while it is only qualitatively good for the \( f \)-modes.

Although, most of our understanding about the oscillations of relativistic stars is due to perturbative studies, recently, the study of stellar oscillations using evolutions of the non-linear equations of motion for the fluid became possible [24, 25, 26, 27, 28]. Finally, differential rotation is another key issue that is believed to play an important role in the dynamics of nascent neutron stars. Actually, it is associated with dynamical instabilities both for fast and slowly rotating neutron stars [29, 30] and affects the onset of secular instabilities [31, 32, 33, 34].

Since rotational instabilities are typically connected with fast rotating stars, it is of great importance to study oscillations of this type of objects. As a first step one can drop the “slow rotation” approximation but still maintain the Cowling approximation i.e. to freeze the spacetime perturbations or in the best case to freeze the radiative part of these perturbations. This was the approach used up to now for most of the studies of the oscillations of fast rotating relativistic stars either in perturbative approaches [35, 36] or in non-linear (but axisymmetric) approaches [37].

If neutron stars rotate rapidly, nonaxisymmetric dynamical or secular instabilities can develop. These arise from non-axisymmetric perturbations which may grow if appropriate conditions met
The amplitude of the emitted gravitational waves can be estimated as $h \sim M R^2 \Omega^2 / d$, where $M$ is the mass of the body, $R$ its size, $\Omega$ the rotation rate and $d$ the distance to the source. This leads to an estimation of the maximum GW amplitude

$$h \approx 10^{-22} \frac{r^2}{1-3kHz} d_{15 \text{Mpc}} M_{1.4M_{\odot}} R_{10km}.$$  \hspace{1cm} (1)

If the instability persists for $n$ rotation periods then the effective amplitude will be $h_{\text{eff}} = h \sqrt{n}$ which means that the source can be detected from distances $d_{\text{eff}} = d \sqrt{n}$. Earlier studies for the efficiency of the secular rotational instabilities [38, 39, 40] suggested, that the previous back of the envelope calculation is correct within an order of magnitude and this prompts for a detailed study of the problem using proper general relativistic hydrodynamics. The ingredients that one needs for a proper estimation are: i) the critical rotational value for the onset of the instability, ii) the growth time of the instability, iii) the viscous damping times associated with the specific instability, iv) the maximum amplitude that the instability may reach before it saturates due to non-linear couplings and v) the waveform of the emitted gravitational wave which is vital for the detection.

In the next section we review the most recent efforts in estimating the critical rotational values for the onset of the secular instabilities for uniform and differentially rotating neutron stars [41, 42, 34] while in the last section we present the recent efforts in understanding the dynamics of magnetars and to reveal their structure via the observed quasi-periodic oscillations.

2. Oscillations and Instabilities of Fast Rotating Compact Stars

It has already been known from the Newtonian case, that rotating stars are secularly unstable to non-axisymmetric perturbations once a dissipative effect extracts energy from the system [43]. For constant-density MacLaurin spheroids, this leads to the well-known transition from the axisymmetric MacLaurin-sequence to the triaxial Jacobi-sequence for a ratio of rotational to gravitational energy of $T / |W| = 0.14$. The precise mechanism of this type of instability is not limited to the Newtonian case though. Is is a generic behaviour of a new class of instabilities which are called rotational dragging instabilities, since everything that is needed for them in order to work is a coupling to some radiation field (which will dissipate energy) and a rotating background that leads to a splitting between pro- and retrograde travelling, non-axisymmetric modes. In GR, the emission of gravitational waves will extract energy from the star and for sufficiently high rotation rates, certain modes may destabilize the star due to this so-called CFS-instability [44, 45], which will then emit a copious amount of gravitational radiation. For more realistic equations of state (EoS) than the constant-density MacLaurin-spheroids, the onset of the gravitational wave-driven instability is actually shifted towards lower values of $T / |W|$ as we will see.

Early Newtonian calculations [46] also suggested, that polytropes with a polytropic index of $N > 0.808$ may never be secularly unstable because for these models, mass-shedding at the equator would set in before the instability regime is reached. General relativistic effects will also slightly change this result. Finally, differential rotation will dramatically change this picture, because depending on the precise rotation law one is using and the actual degree of differential rotation, the redistribution of angular momentum inside the star will lead to strongly deformed stars which can attain much higher rotation rates and an even earlier onset of the CFS-instability in terms of $T / |W|$ when compared to uniform rotation [47, 35, 34].

As already mentioned in Section 1, there are various ways to study neutron star oscillations either via direct time-integration of the full, non-linear equations of general relativity or by using certain simplifying approximations. Neglecting non-linear effects and possible mode-couplings, linear perturbation theory is a powerful tool to obtain mode-frequencies and eigenfunctions of small-scale oscillations around the static equilibrium. In addition, freezing the space-time degrees
of freedom, i.e. working in the Cowling-approximation, has proven to be a quantitatively good approach for high-order pressure modes, g- and inertial modes while it is of limited accuracy for predicting fundamental mode frequencies [48, 49].

In the following discussion, we will mostly focus on the quadrupolar fundamental pressure mode although it should be noted, that other mode classes (g- and inertial modes) may also become unstable at considerably lower rotation rates e.g. [50, 42]. The current understanding is, that viscous effects most likely suppress these instabilities though e.g. [51].

Figure 1. Splitting of the $^2f$-mode for three different EoS. Top panel: Frequencies of co- and counterrotating branches for an inertial observer. Bottom panel: Normalized frequencies in the comoving frame.

Figure 1 shows the splitting of the fundamental quadrupolar mode for three different EoS; a detailed description of the equilibrium models can be found in [41]. The BU sequence is a set of constant energy-density models with a polytropic EoS and a polytropic index of $N = 1$,
while EoS A and EoS II are polytropic fits to realistic equations of state with smaller polytropic indices. As one can see, actually all three sequences become CFS-unstable at a certain rotation rate; for the \( N = 1 \)-polytrope this happens virtually at its mass-shedding limit while for the other, more compact models, the instability occurs well below the Kepler-frequency.

As it turns out, despite the obvious differences in the mode-frequencies for the various EoS in the inertial frame (top panel of Figure 1), when normalized in the comoving frame of reference, the frequencies change nearly in the same manner when rotation is increased (bottom panel of Figure 1). If \( \sigma_0 \) is the f-mode frequency in the nonrotating limit and \( \nu_K \) the Kepler-frequency, for all rotation rates we can write

\[
\frac{\sigma}{\sigma_0} = 1.0 + C^{(1)}_{lm} \left( \frac{\nu}{\nu_K} \right) + C^{(2)}_{lm} \left( \frac{\nu}{\nu_K} \right)^2
\]

and perform a quadratic fitting of the curves in the right panel of Figure 1. We find \( C^{(1)}_{22} \approx -0.25 \) and \( C^{(2)}_{22} \approx -0.38 \) for the \( m = 2 \) solution and \( C^{(1)}_{-2} \approx 0.48 \) and \( C^{(2)}_{-2} \approx -0.55 \) for the \( m = -2 \) branch. This can potentially be used in order to determine stellar parameters like mass, radius and angular velocity once one can actually detect oscillation frequencies of neutron stars.

Differential rotation adds a new degree of freedom to the problem which is of great importance for young hot nascent neutron stars. Depending on the exact rotation law for differential rotation, which is unknown currently, it usually allows for much higher rotation rates than for uniformly rotating stars since the total angular momentum can be disposed in a variety of possible configurations. Here, we focus on the commonly used j-constant law

\[
A^2 (\Omega_c - \Omega) = \frac{(\Omega - \omega)^2 r^2 \sin^2 \theta e^{2(\psi - \nu)}}{1 - (\Omega - \omega)^2 r^2 \sin^2 \theta e^{2(\psi - \nu)}},
\]

where \( \Omega_c \) is the angular velocity along the rotation axis and the parameter \( A \) controls the degree of differential rotation, see also [52].

The splitting of the fundamental mode for various degrees of differential rotation can be seen in Figure 2, where the dashed line shows the limit of uniform rotation. Since there is no unambiguous definition of a global angular velocity any more, we plot the mode frequencies against the ratio of rotational to gravitational energy \( T/|W| \).

As one can see, a higher degree of differential rotation, which is indicated by a larger value of the dimensionless parameter \( \hat{A} \), leads to equilibrium models that can store a lot more rotational energy than the uniformly rotating case and second, the CFS-instability typically sets in at a smaller fraction of the maximum allowed \( T/|W| \), which is indicated by the endpoints of the curves in Figure 2. This behaviour is generic in the sense that it not only applies for the fundamental quadrupolar mode but for high order non-axisymmetric modes as well. To make this point more clear, we can define the dimensionless quantity \( \hat{\beta}_c \) to be the value of \( T/|W| \) at the onset of the CFS-instability, normalized by its corresponding value at the mass-shedding limit.

This is somewhat similar to the normalization we did for the uniform rotation rate in equation (2). It then turns out, that increasing the degree of differential rotation leads to a continuous decrease in the critical value \( \hat{\beta}_c \) not only for the quadrupolar mode but for high order modes as well, for which the secular instability sets in even earlier when compared to the quadrupolar mode; see also Figure 3.

So, in general the onset of the CFS-instability is eased by differential rotation and for stiffer equations of state, these effects are even more pronounced, see [34].

Up to now, we were only considering the f-mode and its instability for uniformly and differentially rotating stars. There is another class of barotropic oscillation modes which only works for rotating stars and which we shortly want to mention here. They are called inertial
modes and are restored by the Coriolis force. Due to their low frequency, they are CFS-unstable already at very low rotation rates, see [54].

In Figure 4 we show the frequencies of the $l = 2, m = 2$ inertial mode, the so-called r-mode, along sequences of different degrees of differential rotation. We normalize them by the central angular velocity $\Omega_c$ of the corresponding background model, as it has already been done in [55]. This kind of normalization is suggested by the relation $\sigma = 4/3 \Omega$ which is valid in Newtonian theory, where $\sigma$ is the r-mode’s angular frequency measured in the inertial frame and $\Omega$ the angular velocity of the star.

First, consider the solid curve representing the rigidly rotation case, i.e. $\tilde{A}^{-1} = 0$. Concerning the value of $\sigma/\Omega_c$ in the non-rotating limit, which is approximately 1.43, we observe a small

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**Figure 2.** Splitting of the $2f$-mode for different degrees of differential rotation for the B sequence. All frequencies are computed in the inertial frame.

**Figure 3.** The critical value for the onset of the instability for different degrees of differential rotation and $m = 2, 3, 4$. 
deviation from Newtonian theory. However, this is consistent with general relativistic corrections to the Newtonian result. As it has been shown in [56], the Newtonian value of 4/3 increases proportional to the frame-dragging potential $\omega$ in the metric.

The curves corresponding to the differentially rotating sequences have lower values, because the central angular velocity increases compared to the uniformly rotating ones, and this effect becomes even stronger the higher the degree of differential rotation is. On the other hand, the angular velocity at the equator, $\Omega_e$, is lowered so that a normalization by this quantity would move the lines in the other direction. Finally, we chose to normalize by the central angular velocity in order to compare qualitatively with Newtonian findings in [55]. We find that the qualitative behaviour is the same.

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**Figure 4.** Frequencies of the r-mode for several sequences with different degrees of differential rotation. The frequencies are normalized by the central angular velocity $\Omega_c$.

3. Magnetar Dynamics

Magnetars are neutron stars with a magnetic field, greatly exceeding $B > 10^{14}$ Gauss. The Soft Gamma Repeaters (SGRs) are astronomical objects with a giant flare activity: they release a huge amount of energy ($L \simeq 10^{44} - 10^{46}$ ergs/s) in few seconds. These giant flares are thought of being associated with starquakes, due to the huge magnetic field and its rearrangement. For this reason, the SGRs are considered to be magnetars.

Up to now, three SGRs have been detected: SGR 05026-66 in 1979, SGR 1900+14 in 1998 and SGR 1860-20 in 2004. In two of those objects (SGR 1900+14 and SGR 1860-20), a tail lasting several hundred seconds has been observed. The study of this part of the spectrum has revealed the presence of quasi-periodic oscillations QPOs (see [60], [64] and [65]), whose frequencies are approximately 18, 26, 30, 92, 150, 625 and 1840 Hz for SGR 1860-20 (with possible additional frequencies at 720 Hz and 2384 Hz) and 28, 53, 84 and 155 Hz for SGR 1900+14.

Since the range in frequencies is so wide, many types of modes have been excluded: for example, the interface modes generated in the layer between core and crust (they have frequencies ranging 10-30 Hz) and the shear modes in the solid crust of neutron stars since their frequencies start from around 100 Hz.

It is believed that, after fracturing of the crust, seismic oscillations could be excited: such oscillations are known as torsional oscillations (t-modes) and depend just on the shear velocity.
\( \nu_s = \mu/\rho \), where \( \mu \) is the shear modulus which takes into account the elastic response of the crust to the oscillations. The t-modes are axial-type oscillation with a typical frequency of \( \sigma = \nu_s/R \) with \( R \) being the radius of the star.

Since the detection of QPOs, many models were constructed which tried to fit those frequencies. The first works focused purely on crustal torsional oscillations, as for example in [62] where a dipole field and a realistic EoS were used. However, not all the frequencies could be explained with such a model: [59] suggested that the observed spectra could be explained via global magneto-elastic oscillations while [61] pointed out that the spectrum could be a continuum. This idea was confirmed in [63], where a 2-dimensional time evolution equation of linearized Alfvén oscillations was used, together with a dipole magnetic field and realistic EoS. However, the two-dimensional equation that has been used there has a pathological behaviour that drives the code unstable and in order to stabilize the problem, a certain amount of artificial viscosity was needed.

In two recent papers, [57] and [58], the use of artificial viscosity was avoided: in the first case, the authors used a simple coordinate transformation which was based on the distribution of the magnetic field lines and which reduces the two-dimensional time-evolution equation of [63] to a one-dimensional equation, also avoiding the use of artificial viscosity while in the second case, the authors used a full non-linear code. In all these papers, the coupling between core and crust was not taken into account: the star was assumed to be a pure fluid. The coupling between crust and core is one of the main open issue in the study of QPOs: it may be able to explain the small gap between the lower frequencies 18 Hz, 26 Hz and/or 30 Hz in the data for SGR 1860-20. In fact, the crust modes are related to the lower frequencies by the following rule [66]:

\[
    t_n = \left[ 1 + a_n (B/B_\mu)^2 \right]^{1/2} t_0 ,
\]

where \( t_0 \) is the fundamental torsional frequency, \( t_n \) indicates the overtones of order \( n \), \( a_n \) is a certain coefficient and \( B_\mu = 4 \times 10^{15} \) Gauss is the magnetic field, measured at the pole. On the other hand, the Alfvén waves in the core seem to form a continuum and they are linked by

\[
    f_n^{\text{even}} = (2n + 1)f_0 , \quad f_n^{\text{odd}} = (n + 1)f_0 , \quad f_n^{\text{close}} = (n + 1)f_0 ,
\]

where \text{even} and \text{odd} indicates whether the boundary condition on the equator is of even or odd parity while the label \text{close} indicates the closed magnetic field lines that close inside the star without reaching the surface and which match with the dipole magnetic field outside the star. In Figures 5 and 6 we show a plot of the frequencies for open and closed lines respectively. If both core and crust frequencies are taken into account, then the complete QPO spectrum could easily be explained. A proper combined study of the coupled core and crust oscillations is still underway. Some preliminary results are shown in Table 1: the frequencies labelled as \( f_{\text{crust}} \) are due to the presence of the crust, while the frequencies labelled as \( f_{\text{crust+core}} \) are present in the interior of the star. The frequencies in bold are approaching the 22, 58 and 116 Hz found in SGRs 1806-20 by [67]. The results in Table (1) seem to confirm the hypothesis, that the coupling between crust and core should lead to extra features in the spectrum [69]. In figure (7) we plot the frequencies in the core (green-dot line) and the extra frequencies given by the presence of the crust (red-continue line).

The study of QPOs in magnetars can constrain the mass and the radius of the neutron star and gives us information about the topology and the strenght of the magnetic field. In fact, taking a model with a given equation of state and performing our time-evolution analysis, we can see if the frequencies that we obtain can fit or no the observed frequencies. If this is the case, then we know the equation of state, the mass and the radius of our star. In our study, we find that the model with a mass \( M = 1.4 - 1.5 \, M_\odot \) and an equation of state not too stiff, may fit better the data.
Figure 5. The QPOs value in the case of a fluid star. The mass of the star is $M = 1.4 M_\odot$ and the model is APR2. The frequencies follow the pattern given in (5) for open lines.

Figure 6. The QPOs value in the case of a fluid star. The mass of the star is $M = 1.4 M_\odot$ and the model is APR2. The frequencies follow the pattern given in (5) for closed lines.

In the study of magnetar dynamics, one must not forget the importance of magnetic field configurations. It is known that different magnetic field configurations could influence the surface temperature of the star and induce anisotropies, see [70]. This effect is more relevant if the magnetic field is confined in the crust: such configurations are called crustal fields and they occur when the core is a type I superconductor. In this case, because of the Meissner effect, the magnetic field is expelled from the core in about $\approx 100$ years.

In a paper by [71], different magnetic field configurations were studied in order to examine if and how they can fit the QPOs observations. The authors consider both a toroidal and a poloidal component of the magnetic field. The study included a configuration that owns a
Figure 7. The QPOs value in presence of the coupling between crust and core. The mass of the star is $M = 1.4M_\odot$ and the model is APR2. It is possible to see extra frequencies showing.

| Model     | $f_{\text{crust+core}}$(Hz) | $f_{\text{crust}}$(Hz) |
|-----------|-----------------------------|-------------------------|
| APR14     | 22.28                       | 16.93                   |
|           | 39.74                       | 31.57                   |
|           | 56.08                       | 45.80                   |
|           | 75.91                       | 62.53                   |
|           | 93.32                       | 80.09                   |
|           | 112.8                       | 96.95                   |
|           | 115.3                       |                         |

Table 1. Frequencies present only in the crust ($f_{\text{crust}}$) and frequencies present in the core and in the crust ($f_{\text{crust+core}}$) for stellar model APR2 ([68]) and a mass of $M = 1.4M_\odot$.

type I superconductor core (with both components of the magnetic field confined to the crust) while another configuration was constructed with the assumption that the magnetic field could permeate the star. They found that only if the magnetic field was permeating the whole star, the observed QPO data can be explained. So the case of a magnetic field solely confined in the crust should be excluded in QPO-studies; actually this result was confirmed in [72].

The most crucial missing points for the gravitational wave research is the absence of proper simulations of the way and the degree of excitation of the density variations. They are ultimately linked with the emission of gravitational waves which, if it takes place, will be a unique observation for astronomy. The event, a flaring magnetar, could potentially be observed in various parts of the electromagnetic and gravitational wave spectrum [73]. Such an observation will provide us with unique constraints on the structure and dynamics of magnetars and it could
be a tremendous boost in the attempt to understand the structure of magnetized neutron stars.

The analysis of data taken during the super-flare event in SGR 1806-20 that took place in December 2004, when LIGO was in operation, revealed no evidence of gravitational wave emission [74, 75]. This is not a surprising result since the actual sensitivity of LIGO at that time was three to four orders of magnitude below the expected sensitivity of the next generation of gravitational wave detectors such as the “Einstein telescope” (ET). Furthermore, a detailed analysis should not be performed only for signals at the observed QPO frequencies alone, since the accompanying gravitational wave signal might be emitted at completely different frequencies.

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