Seismology of magnetars

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Introduction

This thesis contains the results of a PhD project carried out during the past four and a half years at the University of Leiden. The basis for this work are four journal papers on the subject of magnetar seismology. The chapters 1, 2, 3 and 4 are completely or partly based on these articles.

In this introduction, a brief historical overview is given on the subject of neutron stars and in particular a special type of these objects; magnetars. The recent discovery of quasi-periodic oscillations during the afterglows of energetic outbursts on magnetars is reviewed and their importance for our understanding of neutron star interiors discussed.

History

By the end of the 1920s it seemed to many physicists that the physical picture of the structure of atoms was complete or at least nearly correct. Since Rutherford's discovery of the proton in 1918, it was commonly presumed that atoms consist of positively charged nuclei composed of protons and nuclear electrons (the only known sub atomic particles known at the time), surrounded negatively charged electrons circling around the nuclei in tight orbits. The energy levels and spectral frequencies for the hydrogen atom had been successfully reproduced by Schrödinger's quantum mechanical analysis in 1926. However, with the advent of this new quantum theory, the exact composition of the nucleus had become subject of debate. The existence of electrons in the tiny atomic nuclei seemed inconsistent with Heisenberg's uncertainty principle. Moreover, results of nuclear spin measurements of the nitrogen-14 isotope, performed at Caltech in 1929 (Rasetti, 1929), were contradicting predictions of the Rutherford model. To all debate came an end when a series of particle scattering experiments led to the discovery of the neutron in 1932 by James Chadwick. In earlier experiments, German physicists Bothe and Becker (1929) and the French Irène and Frédéric Joliot-Curie (1932) had bombarded beryllium atoms with alpha particles and found that the beryllium gave off 'strongly penetrating radiation' as a result. This radiation, which the Joliot-Curies interpreted as high energy gamma-photons, was shown to be able to eject protons from a paraffin substrate. James Chadwick, highly sceptic about this interpretation, repeated the experiments at his Cambridge laboratory with beryllium and a number of other elements as targets and showed that the outcoming radiation had to consist of electrically neutral particles with a mass more or less the same as protons. The discovery of the neutron, which earned Chadwick the 1935 Nobel Prize in physics, solved all experimental discrepancies that existed within the old Rutherford model and changed our view of the nucleus dramatically.

In 1933, barely a year after the discovery of the neutron, astronomers Walter Baade from Mount Wilson Observatory and Fritz Zwicky from Caltech, presented some extraordinary new ideas at a scientific meeting at Standford University. Zwicky had been working on cosmic rays for a while and had proposed that these highly energetic particles originated from catastrophically exploding stars, which he called supernovae. Together with Baade, who notably had an encyclopedic astronomical knowledge and was aware of historical accounts of new, bright stars that suddenly appeared at the sky before fading away, Zwicky started working on his supernova idea (deGrasse Tyson & Soter, 2001). At the Stanford meeting, the two put forward the hypothesis that these supernovae were in fact the violent transitions from normal stars into an exotic type of compact objects existing almost entirely of neutrons. The amount of gravitational binding energy released during the collapse of a star to nuclear densities, they reasoned, would be sufficient to power the supernova.[1] The

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[1] The possibility of stellar cores at nuclear densities was tentatively suggested a year earlier (short before the discovery of the neutron) by soviet physicist Lev Landau, who contemplated the physical nature of stellar equillibrium: "... the density of matter becomes so great that atomic

idea was met with skepticism and, perhaps partly due to Zwicky's unpopular character[1], didn't gain much acceptance among contemporary astrophysicists. In the years to follow Zwicky, attempting to convince the scientific community of his ideas, would pursue his research on supernovae, unsuccessfully. At the end of the 30s however, the idea of neutron stars, or more correctly compact stellar cores comprised of neutrons, gained some attention from theorists as it was thought that they were potential sources of stellar energy (Landau, 1938). In this line of thought, Robert Oppenheimer and George Volkoff in 1939 investigated the stability of these neutron cores and published the first hydrostatic model of neutron stars.[2] During the late 30s however, nuclear fusion processes became gradually understood and eventually recognized as the fundamental source of power in stars. And so it happened that neutron stars went out of fashion for the next couple of decades.

Until the late 60s neutron stars received little attention, due to their small sizes they were expected to be too faint to be observed by contemporary telescopes (Shapiro & Teukolsky, 1983). However, everything changed when Jocelyn Bell and Antony Hewish from Cambridge University discovered the first radio pulsar in 1967. It was soon realized that the new pulsating source had to be a neutron star.

Neutron stars

A typical neutron star has a mass between 1.2 and 2.0 $M_\odot$ inside a sphere of radius ~ 10 km. It is generally thought that the neutron star core consists of

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nuclei come in close contact, forming one gigantic nucleus". Landau however, did not associate the formation of such "gigantic nuclei" with a catastrophic gravitational collapse of cores, but considered steadily growing dense cores inside ordinary stars as the source of stellar energy. (Landau, 1932, 1938)

[1] Zwicky used to call astronomers at Mount Wilson Observatory "spherical bastards", because "they were bastards no matter how you looked at them" (Kirshner, 2002). Also, Zwicky's relation with his German collaborator Baade, which he falsely accused of being a Nazi, was problematic to say the least. According to Bryson (2003), Zwicky threatened to kill Baade on at least one occasion.

[2] Much to Zwicky's dismay, the authors didn't give any reference to his work, even though Oppenheimer was a direct colleague at Caltech.

mixture of two quantum fluids; superfluid neutrons, which comprise roughly 95% of the mass and superconducting protons (see e.g. Link, 2007). The outer ~ 1 km of the star forms a solid crust consisting of a lattice of heavy nuclei, which become more neutron rich at greater depth. In the inner portion of the crust, beyond a point called ‘neutron drip’, the neutrons leak out of the nuclei, forming a superfluid which coexists with the crustal solid. Neutron stars are penetrated by strong magnetic fields (in the wide range between 10^8 and 10^{15} G), which act to slow down the rotation of the stars: As the star rotates around its axis, the field lines which are anchored to the crust, rotate along with the star. In effect, angular momentum is transported from the star through the rotation induced magnetic stresses (Spitkovsky, 2006).

Although this standard picture is thought to be true for most neutron stars, the different astrophysical sources which are today identified as neutron stars vary wildly in their observational properties. Most types of neutron stars radiate in different parts of the electromagnetic spectrum with rotation rates spanning over three orders of magnitude. Some neutron stars show violent activity in the form of energetic outbursts, while others appear to lead quiet lifes. The largest subclass of neutron stars are the radio pulsars (PSR), which are best observed at radio wavelengths but are also known to pulsate in other frequency bands. A sub-class of radio pulsars are the millisecond pulsars (MSP), which are characterized by their fast rotation, which in many cases seems to originate from accretion powered spin-up. This spin-up might occur during a phase where the neutron star forms a low mass X-ray binary (LMXB): The companion star transfers angular momentum through accretion to the neutron star, which can theoretically spin up to millisecond periods. The persistent radio emission from both PSRs and MSPs is thought to be powered by the rotational energy loss due to magnetic spin-down. Yet another class of radio pulsars are the recently discovered rotating radio transients (RRAT), which seem to switch on and off in an unpredictable manner.

With the rapid developments of X-ray astronomy in the past decade, new varieties of isolated objects have been added to the list of neutron stars. These include the X-ray bright compact central objects (CCO) directly associated with supernova remnants (see e.g. Pavlov, Sanwal & Teter, 2004) and the anomalous X-ray pulsars (AXP) and soft gamma repeaters (SGR) (see e.g. Woods & Thompson, 2004). As can be seen in the P-$\dot{P}$ diagram of figure 1, the AXPs and SGRs having long rotation periods and fast spin-down, form a distinct group of objects relative to the bulk of pulsars. Their extreme spin properties can be explained by tremendously strong (dipole) magnetic field strengths ($B = 10^{14} - 10^{15}$ G). Moreover, their quiescent X-ray luminosities exceed the energy loss due to spin-down by orders of magnitude, implying that instead they might be powered by the decay of a very strong magnetic field. Hence AXPs and SGRs are often referred to as 'magnetar candidates'.

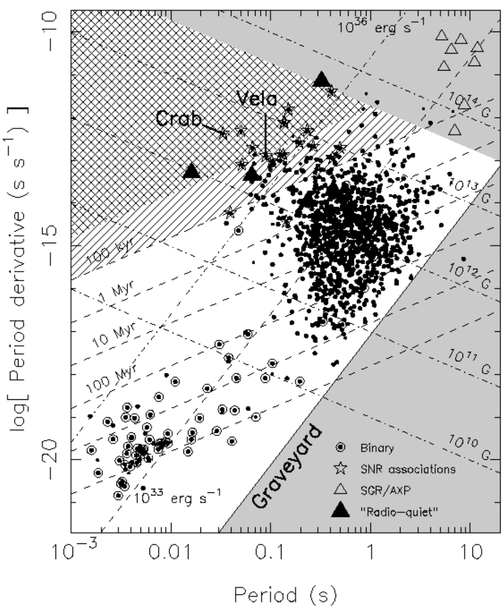

Figure 1: *P-$\dot{P}$ diagram for pulsars. The straight lines in the plot indicate the lines of constant age, the dipolar magnetic field strength and the spin-down luminosity. The grey region indicates areas where radio pulsars are not expected. Magnetar candidates, i.e. AXPs and SGRs are indicated with transparant triangles and are clearly separated from the main distribution of pulsars. (Reproduced with permission from "Handbook of Pulsar Astronomy" by Lorimer & Kramer, 2004.)*

Magnetars

The existence of magnetars was first hypothesized in the early 90s by Duncan & Thompson (1992), who studied dynamo mechanisms in newly born neutron stars. In their famous 1992 paper, they argued that during the first few moments after gravitational collapse, under the right circumstances, a neutron star might be subject to very efficient dynamo action. The first 30 seconds after its formation, strong temperature gradients in the neutron star will drive a strong convection driven by the large neutrino flux. The strong convection, in combination with a very rapid spin ($P \sim 1$ ms) will lead to a very efficient $\alpha - \Omega$ dynamo which could easily amplify the magnetic field to values $B > 10^{15}$ G, at least 3 orders of magnitude stronger than the field strength of an ordinary pulsar. Another possible formation scenario for magnetars, is that they form during the collapse of a strongly magnetized massive star (Thompson & Duncan, 1993) or during the accretion induced collapse of a strongly magnetized white dwarf (Usov, 1992). In these cases, 10^{15} G magnetic fields could be established as a result of conservation of magnetic flux.

Since the early 1990s, it is thought that SGRs and AXPs are neutron stars powered by the decay of very strong magnetic fields. In contrast to radio pulsars, which are powered by the loss of rotational energy, SGRs and AXPs have quiescent luminosities exceeding their spin-down power, indicating that some other source of energy must be at work. Moreover, the SGRs in particular are known to be highly active, showing irregularly recurring short (0.1 s), energetic ($\sim 10^{41}$ erg s^{-1}) outbursts of X-rays and gamma-rays. As Thompson and Duncan (1995) pointed out, several independent arguments support the idea that SGRs are neutron stars with ultra-strong magnetic fields ($10^{14} - 10^{15}$ G); magnetars.[1] Ultra-strong magnetic fields would explain the spin properties and quiescent X-ray luminosities of SGRs. Other arguments in favor of ultra-strong magnetic fields are based on the properties of an extremely energetic outburst (*Giant Flare*) from the source SGR 0526-66, measured on March 5th 1979. This outburst was in fact so energetic, that if it was powered by the decay of a magnetic field, the field has to be $> 10^{15}$ G. On the other hand, similarly strong magnetic fields are required to confine the amount of energy in the tail of the burst and to reduce Compton scattering cross-sections, ex-

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[1] Compelling observational evidence for this hypothesis was found by Kouveliotou et al. (1998), who observed X-ray pulsations with a period of 7.5 s for the soft gamma repeater SGR 1806-20. This discovery provided a ‘missing link’ between SGRs and the persistently pulsating AXPs. It is now generally accepted that both types of sources are magnetars.

plaining the measured hyper-Eddington fluxes (Paczyński, 1992; Thompson & Duncan, 1995). Another interesting observation is that all known magnetar candidates known to date[1] are isolated sources. In their 1992 paper on the formation of magnetars, Duncan and Thompson argued that during the formation several magnetically induced mechanisms could generate large recoil velocities ($\sim$ 1000 km s^{-2}), easily sufficient to unbind the magnetar from a possible companion star.

SGR giant flares and QPOs

On January 7th 1979 the first soft gamma repeater (SGR) was observed with gamma-ray sensors aboard the Soviet Venera 11 space craft, which detected a short, intense burst of soft gamma-rays coming from a source that was identified as a gamma ray burst (then named GB 790107, but now known as SGR 1806-20) (Mazets & Golenetskii, 1981). The January 7th event was followed by an extremely energetic flare on March the 5th that same year from another source. This event, had a peak luminosity roughly three orders of magnitude brighter than the one on January 7th and was followed by 3 minute exponentially decaying afterglow. In the months following the flare, the position of the source (SGR 0526-66) was accurately determined to be near the edge of a young supernova remnant located in the Large Magellanic Cloud (Evans et al., 1980), the distance to the source implying a peak luminosity of 10^{44} erg s^{-1}. Initially, both the January 7th and March 5th events were classified as Gamma Ray Bursts (GRB), but when in late 1983 more bursts occurred from SGR 1806-20, it became clear that this source had to belong to an independent class of objects; Soft Gamma Repeaters (SGR)[2] (Laros et al, 1987).

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[1] To date a total of 16 magnetars are known. 7 Candidate sources are awaiting confirmation: 11 SGRs (7 confirmed, 4 candidates) and 12 AXPs (9 confirmed, 3 candidates). See http://www.physics.mcgill.ca/~pulsar/magnetar/main.html

[2] The distinction between SGRs and GRBs was made due to the repetitive nature of flares: GRBs have never been found to repeat. Also, SGRs flares are characterized by their short duration ($0.1 - 0.2$ s) and relatively soft gamma-ray spectrum, with respect to GRBs.

Giant flares, such as the March 5th 1979 event on SGR 0526-66, are the most energetic bursts occurring on soft gamma repeaters. They are characterized by the sudden release of $> 10^{44}$ erg in hard X-rays during an initial spike of a few tenths of a second, followed by a spectrally softer, decaying, pulsating afterglow, lasting for several minutes. To date, only three such energetic events have been observed, of which the flare on December 27th 2004 from SGR 1806-20 was by far the most powerful, with a peak luminosity of $> 10^{47}$ erg s^{-1}. These events are thought to be powered by a catastrophic global reconfiguration of the magnetic field. Two possible mechanisms that could trigger such a reconfiguration are: (1) An internal mechanism: The strongly wound up internal magnetic field stresses the crust until an instability develops and the crust cracks (Thompson & Duncan, 1995, 2001). (2) An external mechanism: Due to a slow shearing motion of the magnetic footpoints, stresses build up in the magnetospheric field, eventually leading to a

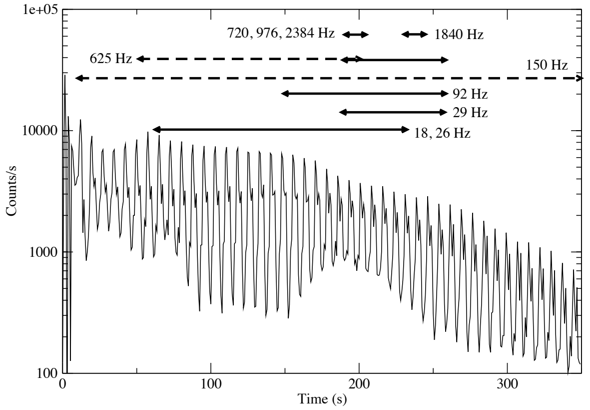

Figure 2: *Light curve showing the X-ray intensity during the afterglow of the December 2004 event from SGR 1806-20. At different time intervals during the afterglow, QPOs at various frequencies are measured as indicated by the arrows. The steady periodic modulations of the curve are due to the* 7.5 s *spin period of the star. (Reproduced with permission from Strohmayer & Watts, 2006.)*

fast reconnection event (Lyutikov, 2006; Gill & Heyl, 2010).[1]

Since the magnetic field is frozen into the solid magnetar crust, it is reasonable to believe that a fast global reconfiguration of the magnetic field triggers strong crustal vibrations. We explore the excitation of magnetar oscillations in chapter 2 of this thesis.

A remarkable discovery was made in 2005, when the analysis of the December 2004 giant flare on SGR 1806-20, revealed the presence of quasi periodic oscillations (QPOs) in the 3 minute afterglow following the event (Israel et al., 2005; Watts & Strohmayer, 2006; Strohmayer & Watts, 2006)[2]. Clear QPOs were found at several frequencies, ranging from 18 Hz to 1800 Hz, showing up at different time intervals during the afterglow (see figure 2). Following this discovery, QPOs at similar frequencies were also found in the 1998 giant flare from SGR 1900+14 (Strohmayer & Watts, 2005). Interestingly, the QPOs in both events appear at specific rotational phases of the stellar rotation, implying an association of the QPOs with specific areas of the neutron star surface or magnetosphere (Watts & Strohmayer, 2006). The physical origin of QPOs is generally believed to be torsional oscillations of the magnetar, which are relatively easy to excite (Duncan, 1998; Levin & van Hoven, 2011; chapter 2 of this thesis). Clearly, a proper explanation of the observed QPOs may give a unique insight in the interior structure of neutron stars.

Seismology of magnetars

In the past decades, the study of stellar oscillations has been a major force driving the advance of knowledge of the interior structures of stars. For example, the extraordinary wealth of oscillation data that exists for the Sun, has provided detailed information about its internal structure and rotation,

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[1] The fast rise time (few microseconds) of the 2004 flare, gives reason to believe that the external mechanism is at play, as the internal mechanism works on the much longer Alfvén crossing time ($\sim$ 0.1 s).

[2] A pulsating component in the light curve of the March 1979 event on SGR 1806-20 was reported in Barat et al., 1983

as well as its chemical composition. Despite the relative scarcity of detected oscillation modes in stars other than our Sun, the study pulsating stars, e.g. RR-Lyrae variables, Delta Scuti stars and Cepheids, has led to considerable understanding of their internal structures and physical processes.

Our current understanding of neutron star interiors however, is much more uncertain. Observed oscillation modes of a neutron star, would greatly help to constrain basic properties like the equation of state, or crustal composition. In the past decades, oscillations of neutron stars have been subject of extensive theoretical study (see e.g. a review by Kokkotas & Schmidt, 1999) and it has become clear that general relativistic effects play an important role in oscillating neutron stars. Some types of modes couple strongly to the space-time continuum and damp on relatively short time scales by emitting gravitational waves. Andersson & Kokkotas (1998) showed that a single observed f-mode and its damping time would be sufficient to determine the mass and radius of the neutron star with errors of only a few percent. Other modes, in particular the r-modes, might be subject to the CFS (Chandrasekhar-Friedman-Schutz) mechanism, which causes a gravitational wave-driven instability (Chandrasekhar, 1970; Friedman & Schutz, 1978; Andersson & Kokkotas, 2001). Clearly, the strong coupling of neutron star oscillations to gravitational waves opens the interesting possibility to perform asteroseismological studies of neutron stars with future gravitational wave detectors. However, the recent observations of magnetar QPOs already enables us to perform asteroseismological analysis of magnetars, provided that we find a correct interpretation of their origin and of the physical nature of the oscillations.

Since the discovery of quasi periodic oscillations in the light curves of SGR giant flares (Barat et al., 1983; Israel et al., 2005; Strohmayer & Watts, 2005; Watts & Strohmayer, 2006), there has been extensive theoretical research of magnetar oscillations. One of the appealing explanations is that the QPOs are driven by torsional oscillations of the neutron star, i.e. nearly incompressible, horizontal oscillations. These modes are free of compressional stresses and do no work against the strong gravitational field of the star and are hence relatively easy to excite (Duncan, 1998). Initially it was thought that the observed oscillations were due to torsional modes that are confined to the elastic neutron star crust (Piro, 2005; Watts & Stromayer, 2006). If this were true, the QPO frequencies would strongly constrain physical parameters in the crust. However, it was realized by Levin (2006) that the presence of an ultra-strong magnetic field ($\sim 10^{15}$ G) would complicate the analysis of the oscillations. Effectively the frozen-in magnetic field couples the motion of the crust to the magnetized core, by launching Alfvén waves (waves with magnetic tension as the restoring force) along the field lines into the stellar interior. In this way the crustal energy is drained on time-scales of < 1 s. Since the magnetar QPOs are observed for hundreds of seconds after the flare, one has to consider the hydro-magnetically coupled crust-core system as a whole. In the past few years several research groups have studied the coupled crust-core dynamics (Glampedakis et al., 2006; Levin, 2007; Gruzinov, 2008; Lee, 2008; van Hoven & Levin, 2011a and b (chapters 3 and 4 in this thesis); Gabler et al., 2011a and b; Colaiuda & Kokkotas, 2011). As pointed out by Levin (2006 & 2007), the dynamics of the crust-core system is further complicated as follows: In a star with an axisymmetric poloidal magnetic field, the Alfvén waves travelling along the field lines of different flux surfaces[1] in the fluid core are decoupled from each other, giving rise to a continuum of Alfvén frequencies[2]. The presence of a continuum in the magnetar core has some important implications for the oscillations: (1) Global modes with frequencies inside the continuum are damped exponentially. This phenomenon is well known in magnetohydrodynamic (MHD) studies (see Goedbloed & Poedts, 2004) and is called *resonant absorption*. It is thought that if the neutrons in the core form a superfluid and the protons a superconductor, the neutron component (~ 95 % of the mass) is dynamically decoupled from the Alfvén motion in the core (see chapter 1). In this case, the fundamental Alfvén frequencies are of the order of ~ 20 Hz for a $B \sim 10^{15}$ G magnetic field. Since the fundamental crustal frequencies are of the same order, resonant absorption is likely to occur for many of the crustal

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[1] The flux surfaces that we consider here, are the axisymmetric surfaces that one obtains by rotating a single fieldline around the polar axis.

[2] Due to the dynamical decoupling of the different flux surfaces, one can view the magnetic field as an infinite collection of strings (field lines), each with unique length and tension. The eigenfrequencies vary in a continuous manner if one moves from flux surface to flux surface

modes. (2) After an initial period of exponential damping, the system settles in a steady state in which it oscillates at frequencies near the edges of the continuum; *edge modes* (Levin, 2007; Gruzinov, 2008; van Hoven & Levin, 2011a (see chapter 3), Gabler et al., 2011a; Colaiuda & Kokkotas, 2011). (3) For simple magnetic field geometries, one may expect the continuum to be piecewise. Gaps in the continuum occur at relatively low frequencies (< 200 Hz) and give rise to undamped motion due to edge-modes, or undamped crustal modes residing in the gaps (van Hoven & Levin, 2011a and b (see chapters 3 and 4); Colaiuda & Kokkotas, 2011).

In recent years the problem of magnetar oscillations has been approached with two distinct computational strategies:

(1) Several groups employed general relativistic *grid based MHD simulations* of magnetars. Sotani et al. (2009); Colaiuda et al., (2009) and Cerdá-Durán et al., (2009) produced continuum Alfvén modes in fluid neutron stars with axi-symmetric magnetic fields. Although these authors did not include a solid crust in their models, their simulations provided important benchmark tests for the ability of their codes to handle complex MHD simulations. Gabler et al. (2011a), (2011b) and Colaiuda & Kokkotas (2011) studied the coupled dynamics of the magnetar crust and core using their relativistic grid-based MHD codes. Colaiuda and Kokkotas (2011) in their study confirmed the existence of undamped motion in a gap between two contiguous continua.

(2) In the approach of Levin (2007), Lee (2008) and van Hoven & Levin (2011a and 2011b: chapters 3 and 4), the authors decomposed the motion of the magnetar into a set of basis functions and studied the dynamics of the coefficients of this series expansion; we refer to this as a *spectral method.* In particular, Levin (2007) and van Hoven & Levin (chapters 3 and 4) decompose the motion of the magnetar into eigenmodes of the‘free crust’ (a crust with no external stresses acting on it) and Alfvén eigenmodes on a dense grid (approaching continuum) of magnetic flux surfaces. Knowing the frequencies and eigenfunctions of the crust and the core flux surfaces, one can recast the problem of magnetar oscillations as a problem of coupled harmonic oscillators. One advantage of this approach is that one can run long and fast simulations of

the oscillating magnetar, without numerical dissipation. Another advantage is that one can sample the neutron star structure with great spatial detail.

To date the results of both the grid-based simulations and the spectral methods seem to be qualitatively in agreement. Simulations show that most oscillatory power resides at relatively low frequencies (< 200 Hz) in gaps or below the lowest fundamental Alfvén frequency. Although the exact results are sensitively dependent on the details of the model (location of gaps, crustal frequencies, etc.), the simulations consistently show no or very low power at higher frequencies. This poses a serious challenge for the interpretation of high frequency QPOs in the tails of SGR giant flares, in particular the strong QPO at 625 Hz. A correct explanation might eventually require one to investigate alternative QPO production mechanisms, or perhaps a somewhat radical revision of the magnetar model. An interesting alternative might be to consider poloidal MHD oscillations as studied by Sotani & Kokkotas (2009). These modes have frequencies in the order of several hundreds of Hz and may be interesting candidates for the high frequency QPOs if their coupling to the other Alfvén modes turns out to be weak.

This thesis

Chapter 1

In chapter 1, we explore some of the implications of the possible coexistence of a neutron superfluid and a type II superconductivity in the cores of neutron stars. If the protons form a type II superconductor, then there should be a strong hydromagnetic coupling between the proton flux tubes and the superfluid vortices. This coupling arises from the fact that not only the flux tubes, but also the superfluid vortices are strongly magnetized due to proton entrainment in the neutron super current. As a result, the vortices are pinned to the charged component (protons, electrons) of the star (Alpar, Langer & Sauls, 1984). We study the effect of strong pinning on the propagation of hydromagnetic waves in the core and derive the corresponding dispersion relations. We discuss two astrophysical implications.

(1) We study Alfvén waves in magnetars, thought to be responsible for quasi-periodic oscillations (QPOs) observed in the light curves of SGR giant flares and show that strong vortex pinning does not lead to significant neutron mass loading of these waves. The resulting Alfvén frequencies are in fact in remarkable agreement with the observed QPO frequencies for a typical magnetar field strength of 10^{15} G, only if the neutrons are dynamically decoupled. However, in rapidly spinning neutron stars with orders of magnitude lower magnetic field strengths, neutron mass loading will play an important role in the Alfvén dynamics.

(2) We show that magnetic stresses in the fluid core tend to suppress the Donnelly-Glaberson instability, a potential source of superfluid turbulence in neutron stars that could act to prevent fast stellar precession. Although this instability is strongly suppressed, we show that fast precession at precession angles greater then ~ 1 degree is unlikely to occur, when the large mutual torques between the superfluid and superconductor can no longer be supported by magnetic tension.

Chapter 2

In chapter 2, we discuss the excitation of two types of magnetar oscillations during SGR giant flares, i.e. torsional modes of the crust and global f-modes. Both types of oscillations are of interest; torsional modes are generally associated with observed magnetar QPOs, whereas f-modes are gravitational wave emitters, potentially detectable by future instruments like Advanced LIGO and VIRGO. In recent years two distinct excitation mechanisms have been proposed that may be at play during giant flares. An internal mechanism (IM): increased magnetic stresses might lead to a global rearrangement of the internal field, culminating in a major rupture of the crust. Or an external mechanism (EM): a large-scale rearrangement of the magnetosphere accompanied by a fast reconnection event.

We argue that, due to the relatively long timescale on which the IM acts (Alfvén crossing time), the excitation of f-modes in the IM is strongly suppressed with respect to their excitation in the EM. We show that even in the EM, only a small fraction of the flare energy is converted to the f-mode. This leads us to the conclusion, that the f-mode is unlikely to be detected by near future gravitational wave detectors like LIGO. Our calculation shows that in contrast to f-modes, torsional modes are strongly excited in both the IM and the EM.

Chapter 3

In chapter 3, we study torsional oscillations of magnetars which are thought to be the origin of QPOs observed during the afterglows of SGR giant flares. The oscillatory dynamics is largely determined by a strong hydro-magnetic coupling between discrete modes of the crust and a continuum of Alfvén modes in the fluid core. Using a simplified model that encompasses the basic characteristics of the system, we numerically simulate the dynamics that follows an initial perturbation of the crust. We find that the motion of the crust can be schematically decomposed into three stages: (1) An initial phase of exponential decay of the crustal motion. The crust transfers a large fraction of its energy to continuum through a mechanism called ‘resonant absorption’. (2) The initial stage of exponential decay stops abruptly and the system enters a stage of slow algebraic decay[1]. (3) After some time the motion of the crust stabilizes and keeps oscillating at a constant amplitude. Fourier analysis of this stage reveals QPOs at frequencies close to the edges of the continuum. We examine these ‘edge modes’ analytically and show that they are a generic, long lived feature of the system.

We set up a realistic magnetar model, consisting of realistic core density profiles and axisymmetric poloidal magnetic field configurations, but with a simplified (infinitely thin) crust. The Alfvén continuum one obtains may, for some field configurations, contain gaps at low frequencies. These gaps give rise to two types of undamped motion: ‘Edge modes’ near the edges of

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[1] For algebraic decay, the damping $\propto t^{-n}$, where n depends on properties of the continuum edges (see Levin, 2007). E.g. turning-point-generated oscillations decay as $t^{-1/2}$.

the continuum bands and crustal modes belonging to the gaps are somewhat shifted in frequency but remain undamped. We show that if the neutrons are decoupled from the Alfvén motion in the core, continuum gaps exist at frequencies below ~ 150 Hz and one may expect QPOs in this regime. If however, the core Alfvén motion *is* mass-loaded by neutrons, the crustal motion should be strongly damped, resulting in negligeble power at QPO frequencies. We thus argue, that the observed QPOs provide evidence for the dynamical decoupling of protons and neutrons. Although our model might account for the observed low frequency QPOs, the general absence of gaps above ~ 150 Hz in our models poses difficulties for the interpretation of some high frequency QPOs, notably the strong 625 Hz QPO. A satisfactory explanation may require either a magnetospheric production mechanism, or possibly a somewhat radical revision of the magnetar model.

We discuss the important issue of magnetic field tangling. We argue that if the field is tangled, the role of the Alfvén continuum will be limited to small scale flux tubes and the tangling will create a dense grid of large scale discrete modes with frequency separations depending on the degree of tangling. We show that this discrete grid of frequencies is in fact so dense (~ 20 Hz), that for high frequency crustal motion it would effectively act as a continuum.

Chapter 4

In chapter 4, we improve the magnetar model from chapter 3 in two ways: First, we replace the infinitely thin elastic crust by a magnetized crust of finite thickness and realistic equation of state. Second, we substitute the Newtonian equations of motion for the crust and the core by general relativistic ones.

As in chapter 3, we set up a spectral computational framework in which the magnetar's motion is decomposed into a series of basis functions which are associated with the crust and core vibrational eigenmodes. We derive general relativistic equations of motion for the magnetized, elastic crust and for the magnetic core. By coupling the crustal modes to the Alfvén modes of the core we obtain a fully relativistic dynamical model of a magnetar which allows long and fast simulations of the magnetar motion without numerical dissipation, while using a very fine sampling of the stellar structure.

We show that in the presence of strong magnetic fields, the crustal modes with one ore more radial nodes become confined to a narrow region near the equator. In this region the horizontal magnetic field creates a magnetic tension-free cavity for modes with radial nodes, which are reflected back to the equator at higher lattitudes, where the field becomes more radial. Due to this confinement, the hydro-magnetic coupling to the Alfvén continuum is reduced, however, their energy is still drained on very small time-scales. Qualitatively, the results of our simulations are similar to the ones in chapter 3. In the appendix of chapter 4 we derive an analytical expression for the damping rate of a crustal mode that is resonantly absorbed by the continuum.

Acknowledgements

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