

## HABILITATION SUMMARY

1. *Name:* Brynmor, Dylan Luigi **Haskell**

2. *Scientific Titles:*

- **M.Sc. (Laurea) in Physics**, University of Pisa, Italy, 2003  
Thesis Title: Merging the Perturbative and the Post-Newtonian approaches in the study of the coalescence of neutron star binary systems  
Thesis Supervisor: Prof. Valeria Ferrari (University of Rome 1 'La Sapienza')
- **Ph.D in Applied Mathematics**, University of Southampton, UK, 2007  
Thesis Title: Gravitational Waves from Deformed Rotating Neutron Stars  
Thesis Supervisor: Prof. Nils Andersson

3. *Employment in research institutions:*

- University of Southampton, UK: Temporary Lecturer: 2007
- University of Southampton, UK: Postdoc, 2007-2010
- University of Amsterdam, The Netherlands: Marie Curie Fellow, 2010-2012
- Albert Einstein Institute (Max Planck Institute for Gravitational Physics), Golm, Germany: Junior Scientists 2012-2013
- The University of Melbourne, Australia: ARC DECRA Fellow 2013-2016
- Nicolaus Copernicus Astronomical Center, Polish Academy of Sciences, Warsaw. Poland: Assistant professor & Marie Curie Fellow since 2016

4. *Habilitation achievement:*

- Title:  
**Gravitational Waves as probes of Neutron Star interiors**
- Publications:  
[P1] Haskell, B., Andersson, N., Passamonti, A., 2009, 'r-modes and mutual friction in rapidly rotating superfluid neutron stars', MNRAS 397, 1464  
[P2] Passamonti, A., Haskell, B., Andersson, N., 2009, 'Oscillations of rapidly rotating superfluid stars', MNRAS 396, 951  
[P3] Haskell, B., Andersson, N., 2010, 'superfluid hyperon bulk viscosity and the r-mode instability of rotating neutron stars', MNRAS 408, 1897  
[P4] Haskell, B., Patruno, A., 2011, 'Spin Equilibrium with or without Gravitational Wave Emission: The Case of XTE J1814-338 and SAX J1808.4-3658', ApJ Lett. 738, L14  
[P5] Haskell, B., Degenaar, N., Ho, W.C.G., 2012, 'Constraining the physics of the r-mode instability in neutron stars with X-ray and ultraviolet observations', MNRAS 424, 93  
[P6] Haskell, B., Ciolfi, R., Pannarale, F., Rezzolla, L., 2014, 'On the universality of I-Love-Q relations in magnetized neutron stars', MNRAS 438, L71  
[P7] Haskell, B., Glampedakis, K., Andersson, N., 2014, 'A new mechanism for saturating unstable r-modes in neutron stars', MNRAS 441, 1662  
[P8] Haskell, B., 2015, 'R-modes in neutron stars: Theory and observations', IJMPE 24, 1541007  
[P9] Haskell, B., Patruno, A., 2017, 'Are Gravitational Waves Spinning Down PSR J1023+0038?', Phys.Rev.Lett 119, 161103

MNRAS = Monthly Notices of the Royal Astronomical Society

ApJ Lett. = Astrophysical Journal Letters

Phys.Rev.Lett. = Physical Review Letters

IJMPE = International Journal of Modern Physics E

5. *Summary of achievement:*



## I. INTRODUCTION

Neutron Stars (NSs) are one of the most exciting nuclear physics laboratories in the universe. The density in the core of these very compact objects (comprising roughly one and a half solar masses in a ten kilometre radius) can exceed nuclear density by an order of magnitude and offers the only direct probe of the state of matter at high densities and low temperatures. The temperatures of these stars are well below the Fermi temperature for the different constituents and so large scale superfluid components are expected in the interior. The study of neutron stars is thus complementary to ongoing terrestrial experimental efforts and allows us to probe an entirely different aspect of the strong interaction, at high temperatures and low densities.

The recent detection of Gravitational Waves (GWs) by Advanced LIGO [1] has opened an entirely new window to study NSs. Gravitational Waves are a prediction of Einstein's theory of General Relativity: they are waves in spacetime sourced by violent astrophysical events (such as black hole or neutron star mergers or supernovae) that propagate at the speed of light and interact very weakly with matter, thus allowing us a 'clean' view of the extreme astrophysical objects they originate from.

NSs are expected to be prolific GW emitters [2]. Binaries containing NSs are one of the main targets for Advanced LIGO, and the recent detection of a NS-NS inspiral in GWs, with associated electromagnetic detections, is already changing our understanding of binary evolution and nucleosynthesis in the universe [3, 4]. The GW signal is still be a 'chirp' (i.e. a signal that increases in frequency and amplitude before the merger), as in the black hole case, but in the case of a NS binary it carries a distinct signature of the star, and in particular of its tidal deformability, and can lead to constraints on the equation of state of dense matter in the interior [3]. Furthermore NS are expected to emit also 'continuous' GW signals, due to non-axisymmetric deformations (or 'mountains') or unstable modes of oscillation [5], as we shall see in detail in the following. Finally, although they are not the object of the studies described here, NSs can contribute to an astrophysical stochastic background of GWs, and may emit bursts of gravitational radiation, not only when they are born in a supernova explosion, but also in coincidence with glitches or magnetar flares [2].

The signals we are discussing are, however, very weak and to extract them from the noisy output of the detectors precise templates obtained from mathematical models are needed. It is thus crucial to understand which aspect of neutron star structure will have the greatest impact on the different kinds of signal and to model the different GW emission mechanisms.

During my PhD and subsequent postdocs I have pioneered many of the techniques that are required to model the multi-component superfluid neutron stars and their GW emission. I will first shortly review the work of my PhD, and then discuss in detail the contributions to gravitational wave astronomy made during the post-doctoral period, and in particular in the papers presented here [P1-P5].

## II. SUMMARY OF DOCTORAL WORK

My PhD, at the University of Southampton under the supervision of Prof. Nils Andersson, focussed on gravitational wave emission from deformed rotating neutron stars. One of the main GW emission mechanisms that could be at work in these systems is a deformation, or 'mountain', on the star that causes its shape to not be spherical, leading to a time varying quadrupole as the NS rotates. In particular I have estimated the maximum size of a "mountain" that can be sustained by the crust of an accreting neutron star [6] or by the core in the presence of a quark condensate [7], and the effect that the magnetic field will have on the shape and quadrupolar deformation of the star [8]. My work has shown that crustal mountains may be large enough to be detected by Advanced LIGO in future observational runs, and will be good targets for next generation detectors such as the Einstein Telescope, as will deformations of the core. Furthermore these mechanisms could lead to strong enough emission to set the spin period of accreting neutron stars in Low Mass X-ray Binaries. It has, in fact, been suggested that the lack of pulsars spinning with frequencies above a KHz (which would still be well below the Keplerian breakup frequency for realistic NS equations of state) is due GW torques, sourced by mountains or unstable modes, preventing the NS from spinning up to such high frequencies. Physically, a mountain would be built up due to asymmetries in the accretion flow and the composition of the crust. As accreted material is pushed deeper in the crust, such asymmetries lead to further asymmetries in heating due to pycno-nuclear reactions, and thermal and compositional gradients in turn source quadrupolar deformations, i.e. 'mountains' [9]. Accreted material spreading on the star will also compress magnetic field lines, locally enhancing the field strength to the point at which it can confine material and support a mountain [10]. During my PhD I have studied this scenario in detail and have found that more refined modelling of the accretion torques, that includes

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radiation pressure for high accretion rates, and magnetic torques in the disc, can explain the cutoff in observed spin distribution without invoking strong gravitational emission [11], thus making it crucial to theoretically model the mechanisms that give rise to a mountain, in order to select targets for gravitational wave searches.

### III. THE EFFECTS OF MAGNETIC FIELDS ON THE GW SIGNALS FROM NS INSPIRALS [P6]

Observational constraints on NS signals, such as mass and moment of inertia measurements in binaries already allow to put limits on the equation of state of dense matter in the stellar interior, and future measurements of neutron star radii with NICER [12] will allow to further constrain the theoretical models. Detections of GW signals from NS inspirals add to this picture by allowing us to measure spin, quadrupolar deformation and the tidal Love number of the star [13]. The first detection of GWs from a NS system has already allowed to set constraints on the tidal deformability of the star, thus constraining the equation of state [3].

In order to break degeneracies in the GW signal and extract parameters, Yagi and Yunes [14, 15] first showed that one can use the so-called I-Love-Q relations, i.e. universal relations between the moment of inertia ( $I$ ), tidal Love number and quadrupole ( $Q$ ) of the star, which for slowly rotating, un-magnetised NS are roughly independent from the equation of state. With the use of these relations it is then possible to break degeneracies between parameters in the GW signal, and measure spins of NSs. It is also possible to conduct tests of General Relativity, possibly also distinguishing strange stars from NSs [14]. Nevertheless NS are strongly magnetised systems, with magnetic fields of the order of  $B \approx 10^{12}$  G for radio pulsars and up to  $B \approx 10^{15}$  G for magnetars. It is well known that magnetised neutron stars will not be spherical [16] and the magnetic field will generate a quadrupole and create deviations from the universal I-Love-Q relations. It should be noted, in fact, that while the influence of the equation of state is weak on simple magnetic field configurations, different geometries of the field, that will depend also on the evolutionary history of the system, will lead to different relations between the quadrupole moment and the moment of inertia. In particular it is possible that in slow enough systems the quadrupole will be completely dominated by magnetic effects, especially if the interior field is significantly stronger than the externally inferred dipole, as a number of models predict [17]. On the one hand such a situation would lead to the erroneous determination of parameters, such as the spin of the star, from the GW signal, if the standard I-Love-Q relations are used in the analysis. On the other it opens the prospect for constraining the geometry and structure of neutron star magnetic fields from GW observations.

In [P6], together with my collaborators at the Albert Einstein Institute (Max Planck Institute for Gravitational Physics) in Golm, Germany, we calculated, in full general relativity, the relation between the quadrupole moment  $Q$  and the moment of inertia  $I$  for NS with either purely poloidal or purely poloidal magnetic fields, making use of the publicly available LORENE (<http://www.lorene.obspm.fr>) library (MAGSTAR code) and for a more realistic twisted torus configuration [17] (in which a poloidal component of the magnetic field coexists with a strong interior toroidal component).

The relation between  $Q$  and  $I$  was calculated for 5 equations of state, 4 of which obtained from microphysical models: the APR EOS [18], the BBB2 EOS [19] the GNH3 EOS [20] and the SLy4 EOS [21], and also for an  $n = 1$  polytropic EOS. In general we find that for purely poloidal or purely toroidal magnetic fields the approximate universal relation of Yagi and Yunes is recovered, but for the more realistic twisted torus models the configuration of the field itself depends on the EOS and universality is lost. For rapidly rotating stars, however, the quadrupole is dominated by the rotational contributions and we find that for systems with fields  $B \lesssim 10^{12}$  G and rotational periods smaller than a few second, the universal I-Love-Q relations can be used. This luckily suggests that for most NS binary systems of interest for LIGO these relations can be used. However not for all. For example in the double pulsar PSR J0737-3039, pulsar B has an estimated field strength of  $B \approx 10^{12}$  G, and is currently spinning with  $P = 2.77$  s, and will have slowed down to  $P = 3.9$  s before merger (if we neglect the possibility of field decay). In this case its quadrupole will be dominated by magnetic field effect. Further higher-order correction will also affect the Love number, as will the presence of higher multipoles of the magnetic field, so great care must be taken in selecting NS systems in which to use I-Love-Q relations, both to extract parameters from GW signals and for test of general relativity.

This work has formed the basis of many subsequent studies in the applicability of I-Love-Q relations in GW astronomy, and, at the time of writing, has been cited 51 times (NASA ADS).

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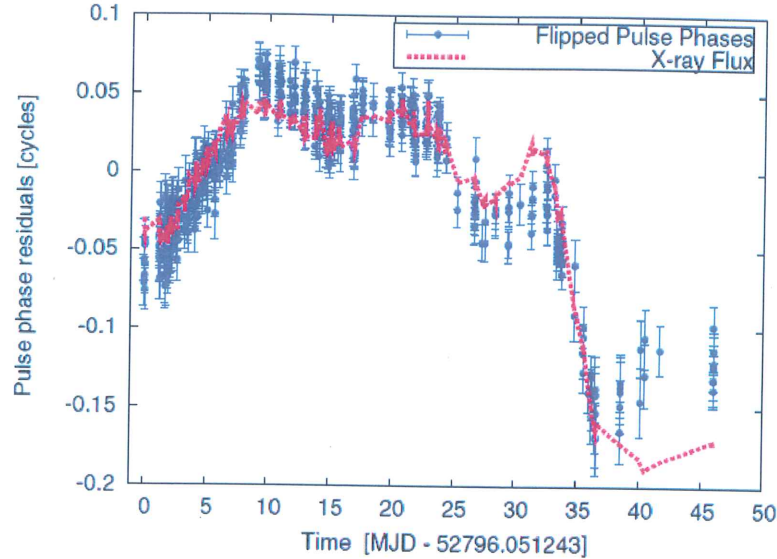


FIG. 1. Phases residuals (with the reversed sign) for the fundamental frequency of J1814 (blue dots), and overplotted (red line) the 2.5-15 keV light curve in arbitrary units. The correlation between the X-ray flux and the phase can be clearly seen, even on short timescales, with slight deviations only at the end of the outburst for low flux levels.

#### IV. GRAVITATIONAL WAVE EMISSION FROM MOUNTAINS IN LMXBS [P4, P9]

Low Mass X-ray Binaries (LMXBs) were first considered as GW sources to provide a solution to an observational puzzle. In these systems a compact object (in the case of interest a NS) is accreting from a less evolved companion. The angular momentum transferred to the NS can thus spin it up to millisecond periods, which is the mechanism by which we believe most millisecond radio pulsars to be created [22–24]. In principle it should thus be possible to spin up the star to close to its breakup frequency, which for realistic equations of state is generally above  $\approx 1500$  Hz (see [25, 26] for a recent assessment of the problem and a discussion on the effect of transient accretion). The observed spin distribution of NSs in LMXBs and in radio-pulsars, however, suggests a cutoff in the spin distribution at around  $\nu \approx 750$  Hz, with indications that in the accreting systems there is a sub-population of fast systems narrowly distributed around  $\nu \approx 600$  Hz [27]. This requires an additional spin-down mechanism that sets in sharply at high frequencies, and GW torques could naturally become strong enough to provide such a mechanism: ‘mountains’ large enough can, in fact, be sustained by the crust [6, 9] or possibly magnetic field of the star [10], and unstable modes of oscillation of the star could also radiate GWs at the required rate [28, 29]. The accretion torques and the interaction between the disc and the field are, however, also likely to contribute to the spin-equilibrium of the systems [11] and a more detailed assessment on the exact mechanisms that would give rise to GW emission is necessary in order to understand which systems could be emitting GWs and should be targeted by Advanced LIGO.

To study this problem in [P4], together with Dr. Alessandro Patruno in Amsterdam, we considered two particular sources: XTE J1814-338 (from now on J1814) and SAX J1808.4-3658 (from now on J1808). Both systems are peculiar in as much as, during an accretion outburst, upper limits can be placed on the spin-up torque, which are lower than what standard accretion theory could predict. This is not a simple measurement and requires care, as in both system timing reveals that the phase of the signal is proportional to the observed X-ray flux, as can be seen in figure (1) for J1814. This is not what is predicted by standard accretion theory, which predicts that the second derivative of the phase (i.e. the frequency derivative) should be proportional to the observed flux. We are thus likely to be observing the accretion hotspot wandering on the surface (as observed also in theoretical simulations [30]) and not the spin-evolution in the system. The correlation between flux and phase is, however, to good approximation linear and can thus be used to clean the phase residuals and time the system. Our analysis in [P2] leads to an upper limit of  $|\dot{\nu}| \lesssim 1.5 \times 10^{-14}$  Hz/s for the 2003 outburst of J1814, while standard accretion theory would predict  $\dot{\nu} \approx 4 \times 10^{-14}$  Hz/s. Similarly timing of J1808 during six outbursts since 1996 leads to upper limits on the spin up/down during accretion of  $|\dot{\nu}| \lesssim 2.5 \times 10^{-14}$  Hz/s, with standard accretion theory predicting  $\dot{\nu} \approx 9 \times 10^{-14}$  Hz/s for these outbursts.

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If the systems are not spinning up at the predicted rate an additional contribution to the torque should be present, and in [P4] we consider the possibility that GWs may be providing this. However for both systems the outbursts are not long enough, given the accretion rate, to build a large enough mountain in the crust (these would be due to asymmetries in heating as the accreted material undergoes reactions in the crust [31], that create compositional asymmetries and source crustal quadrupoles), and we expect the mountain to be washed away on a thermal timescale (of approximately a year for the densities we are considering), so that the mountain has to be built again at each outburst. For J1808 we can be certain this is the case as observations over multiple outbursts constrain the spin-down rate in quiescence and exclude the presence of large quadrupoles that would lead to rapid spin-down [32]. Magnetic mountains are also excluded due to the low accretion rate and low inferred dipole magnetic fields, as are unstable r-modes, as the shear due to a mode large enough to balance the accretion torque would heat the star up to a temperature higher than observed for both these systems. Despite the uncertainties GW torques would thus appear an unlikely explanation for the behaviour of these two systems.

In [P4] we then consider whether the interaction between the disc and the star could explain the changes in accretion torque. We first of all assume the reflare observed at the end of outbursts in both systems are likely to signal the onset of a propeller phase, in which matter is expelled from the system and accretion is centrifugally inhibited. If we thus take the maximum flux for which reflare are present as the flux at which the edge of the disc is rotating at the same rate as the star, we can estimate the spin-equilibrium flux for both systems making use of the accretion model developed during my PhD [11], which accounts for the effect of magnetic fields in the disc and radiation pressure. We find that in both cases the difference between equilibrium flux and the average flux for the outburst is less than 10%. Such proximity to the equilibrium flux leads to a reduction in the torque, which is compatible with the observed upper-limits. We thus propose this explanation for the behaviour of the system and find it unlikely that either J1808 or J1814 could be emitting GWs at a significant enough level to be detected by Advanced LIGO or future detectors such as the Einstein Telescope. Despite the negative result for GW emission, this paper was the first to analyse in detail *physical* GW emission mechanisms (rather than simply rely on upper limits, such as assuming that accretion torques are balanced by GW torques) and has led to observations of a similar behaviour in the system IGR J18245-2452 [33].

Another peculiar system we analysed in [P7] is the transitional pulsar PSR J1023+0038, that shows transitions between an LMXB phase in which it accretes and is visible as an X-ray pulsar, and a radio phase in which accretion has shut off and the star can be timed in radio. It is observed that the spin down rate is 27% faster in the LMXB phase than in radio, an observation that is difficult to reconcile with standard accretion models [34]. In [P7] we show that in this case GW torques can explain the observed behaviour, and a crustal mountain built by accretion during the outburst can quite naturally provide the required spin-down, without any need for fine tuning. Although the expected signal is weak (corresponding to an ellipticity of  $\epsilon \approx 5 \times 10^{-10}$ , or equivalently a strain  $h \approx 6 \times 10^{-28}$ ) and not currently detectable by LIGO, additional observations in the next radio phase will allow us to confirm or reject this scenario, thus providing accurate constraints for the level of asymmetry to expect in accreting systems. If the asymmetries we predict in PSR J1023+0038 are typical of the population, it is likely that systems accreting at a higher rate, and for longer periods of time, harbour mountains large enough to lead to detectable GWs.

In [35] [note that this paper is not included in the achievement list, as some authors have left academia. It has been impossible to obtain a full list of authorship declarations] I consider the full sample of accreting systems, and estimate the detectability of GWs from mountains in known systems. Two mechanisms are considered: ‘thermal’ crustal mountains, i.e. mountains sourced by asymmetries in heating due to pycno-nuclear reactions that occur as accreted matter is pushed into the crust, and ‘magnetic’ mountains, i.e. mountains supported by magnetic stresses. For magnetic mountains the situation is not very promising, as the mountain would only be large enough to be detected if these systems (that in general have inferred exterior magnetic fields of the order of  $B \approx 10^8$  G) have buried fields of the order of  $B \approx 10^{12}$  G, which is in contradiction with the results of obtained in numerical simulations, for which field burial cannot reduce the exterior dipole more than 2 orders of magnitude [36]. For crustal mountains the situation, on the other hand, is quite promising. While in transient systems, that have short periods of accretion followed by long periods of quiescence, the mountain is likely to dissipate on a thermal timescale of the deep crust (of order years) during quiescence; for persistently accreting systems a large mountain can be built, up to the maximum size that the crust can sustain without cracking. This not only would be a detectable source for Advanced LIGO (and easily detectable for future detectors such as the Einstein Telescope), but would also lead to a GW torque which is stronger than that needed for spin-equilibrium, as can be seen in figure (2). The star could thus be spinning down during accretion, contrary to what standard accretion theory predicts. This prediction cannot be currently tested, as none of the systems we consider are X-ray pulsars; we know their period from observations of burst oscillations in the tail of X-ray bursts. If, however, pulsations were to be detected from one of these systems in the future, timing could

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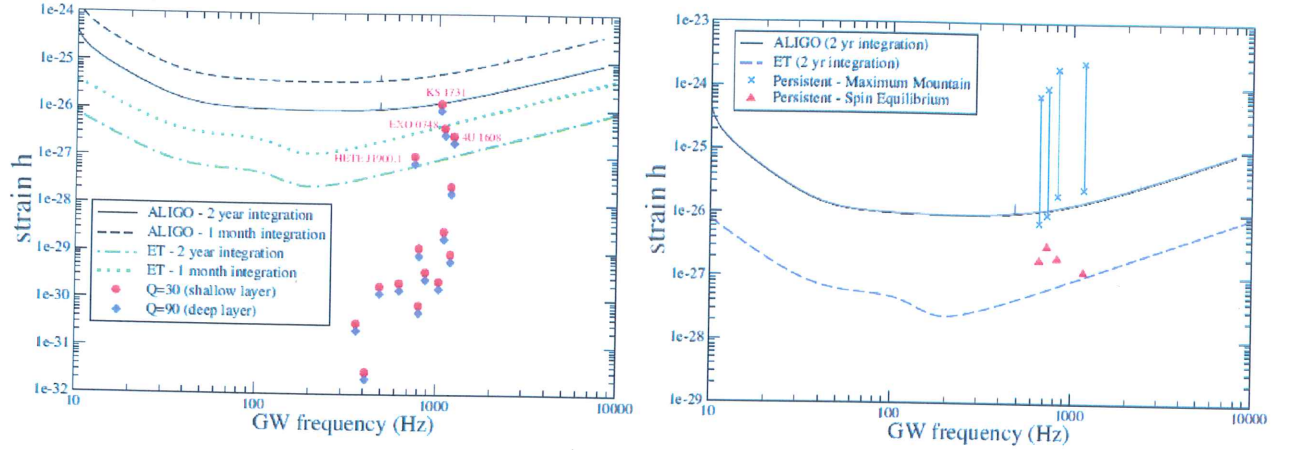


FIG. 2. GW strain versus frequency for mountains in the systems considered in [35]. Transiently accreting sources are shown in the left-hand panel we show transient sources, for two models, one with a shallow ( $Q = 30$  MeV) and one with a deep ( $Q = 90$  MeV) capture layer. In the right-hand panel we show the persistent sources, for which we show the maximum mountain the crust can sustain (crosses), and the mountain that would give spin equilibrium from torque balance between GWs and accretion (solid triangles). The bars indicate the range given by uncertainties on the breaking strain and equation of state.

constrain the size of the GW mountain.

## V. THE ROLE OF THE GW DRIVEN R-MODE INSTABILITY IN LMXBS [P1, P2, P3, P5, P7, P8]

Mountains are not the only mechanism that can lead to GW emission in rotating NSs, and as already mentioned the other main emission scenario is that of modes of oscillation growing to large amplitude and leading to mass and current quadrupoles. The main candidates for observable signals are the fundamental, or  $f$ -mode, which however will be damped by superfluid mutual friction in mature neutron stars (but may play a role in newly born stars and immediately after a merger), and the  $r$ -mode, a toroidal mode of oscillation for which the restoring force is the Coriolis force (analogous to Rossby waves in the Earth's oceans). Pressure, or  $p$ -modes will be at frequencies too high for ground based detectors, and have a weaker coupling to gravitational radiation and stronger viscous damping than the  $f$ -mode. Gravity, or  $g$ -modes will also be present in a thermally or compositionally stratified NS, and will couple to inertial modes for rapid rotation as we discuss in [37], although they are likely to be more strongly damped than the  $r$ -mode [38].

The  $r$ -mode, in fact, despite radiating via the weaker current quadrupole moment, rather than the mass quadrupole, is generically unstable to GW emission due to the Chandrasekhar-Friedman-Schutz (CFS) instability (for a recent review see [P8]), thus growing to large amplitudes in a large fraction of parameter space in which bulk and shear viscosity are unable to damp it efficiently. In a superfluid star, however, there are additional degrees of freedom as the superfluid can flow relative to the normal components of the star. This also opens up a new dissipative channel, allowing for vortex mediated mutual friction to damp the modes. In [P1], together with my collaborators in Southampton, we studied the effect of mutual friction on the  $r$ -mode instability, and found that standard mutual friction mechanisms in the core, where the main effect is due to electron scattering off vortex cores, are much weaker than shear viscosity, which is the strongest source of damping at low core temperatures (below  $10^9$  K). Much stronger mutual friction, such as that due to vortex/flux tube cutting in a superconducting core, can dominate the damping rate, and may even set the maximum saturation amplitude for the mode [P7]. We show, in fact, in [P7], by building on the results of [P1], that if vortices are pinned to flux tubes the  $r$ -mode can grow. To leading order protons and neutrons move together, however at higher order in rotation counter-moving motion develops and grows proportionally to the mode amplitude. Eventually the counter-flow is strong enough to unpin vortices, that cut through flux tubes exciting Kelvin oscillations and rapidly damping the mode, thus setting an effective saturation amplitude. Our analytic results, obtained for slow rotation in [P1] were also extended to rapid rotation with the use of a numerical code developed in [P2], which confirmed that the analytic results are a very good approximation for rotation frequencies below 500 Hz, with differences of less than 2% with the numerical rapid rotation case. At higher frequencies higher order corrections are necessary to accurately track the frequency of the mode. Nevertheless, for observed systems with

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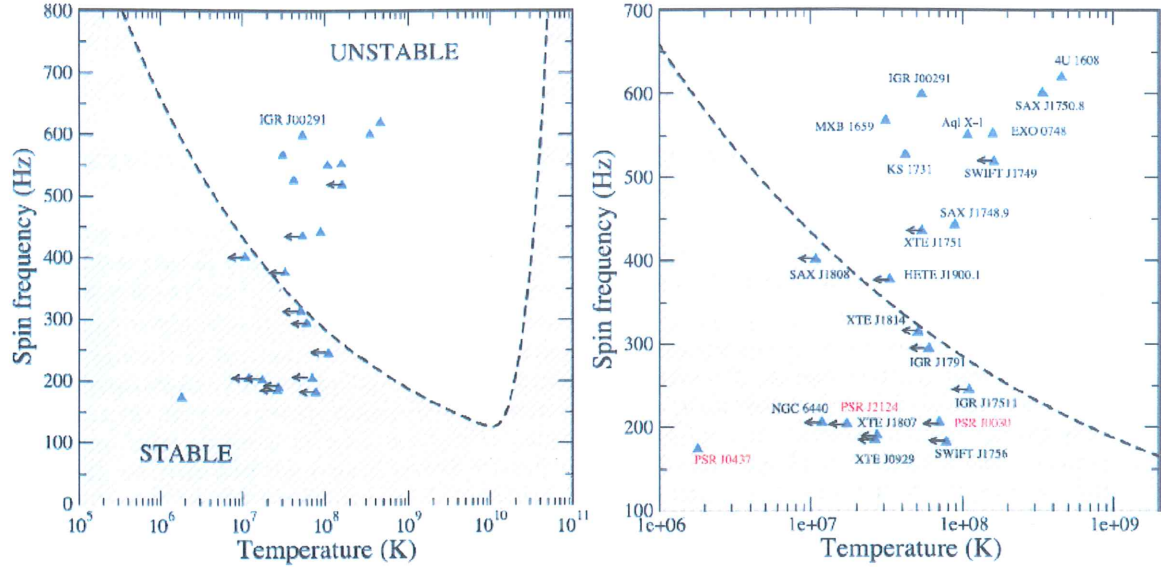


FIG. 3. The  $r$ -mode instability window for a minimal neutron star model, containing no exotic particle, large scale superfluid degrees of freedom or magnetic fields. The mode is stable in the shaded region, unstable in the unshaded part of the plot. The points are the measured temperatures (of the core - assuming a model envelope, as explained in detail in [P5]) and spin-frequencies of LMXBs. The right hand panel is a zoom that allows to better see individual systems

frequencies less than 750 Hz (the fastest currently known pulsar rotates at 716 Hz), the error involved in using the analytic slow rotation expressions is still less than 10%.

In [P3] we also studied additional bulk viscosity due to the appearance of hyperons in the core of a superfluid star. We find that hyperons can strongly modify the instability window, leading to much stronger damping at lower temperatures, and superfluidity, while it does not alter the qualitative picture, can induce large quantitative differences, due to the additional degrees of freedom.

The analysis up to now has been theoretical. We have seen that uncertainties in the neutron star interior equation of state, which also affect whether hyperons appear at high densities and the effect of mutual friction, lead to uncertainties determining in which regions of parameter space the  $r$ -mode is unstable and will lead to GW emission, and in which it is strongly damped. In [P5], together with X-ray astronomers in Amsterdam, I used for the first time X-ray data from Low Mass X-ray Binaries, in particular measurements of spins and surface temperatures, to constrain the physics of the  $r$ -mode instability.

In figure (3) a typical  $r$ -mode instability window for a standard neutron star, composed of neutrons, protons and electrons with no exotic particles or non-standard mutual friction, is plotted. The shaded part is the region in the spin-frequency vs temperature plane in which the mode is damped, while above it it can grow and radiate GWs. As a NS in an LMXB spins up due to accretion it enters the unstable region and the mode grows, while the star heats up due to viscous heating. Eventually neutrino emission will halt the thermal runaway, the star spins down due to GW emission and the cycle starts again. However, if the saturation amplitude of the mode is large the system will enter into the instability window but the duty cycle will be short, with approximately less than 1% of the life-time of the system spent emitting [39]. If, on the other hand, the saturation amplitude is small as predicted by calculations of non-linear couplings to higher order modes [40], the system never moves far from the edge of the unstable region. In either case, it is highly unlikely to observe systems in the unstable region.

In figure (3) we can see clearly that once the instability window is populated with observations of LMXBs (assuming an accreted envelope to estimate the internal core temperature from the observed surface temperature), several systems are in the unstable region. The conclusion is that the simple neutron star model that is often used is not consistent with observations and that either additional physics is needed to create extra damping, e.g. additional viscosity due to hyperons or vortex flux/tube crossings, or mode resonances in the crust, or the saturation amplitude of the  $r$ -mode is much smaller than currently predicted, and the mode can be unstable, but is never large enough to affect either the spin or thermal evolution of the star, as I summarised in [P8].

This was the first paper to use X-ray observations to constrain GW physics and raise the important issue of the

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discrepancy between observations and standard theoretical models, and, to date has been cited 58 times (NASA ADS).

## VI. OTHER TOPICS OF INVESTIGATION - PULSAR GLITCHES

Gravitational Waves are not the only probe of neutron star interior structure. In particular glitches, i.e. sudden jumps in the frequency of pulsars observed mainly in radio (but now also seen in X-rays and gamma rays), are thought to be a large scale, observable consequence of superfluid paring on the microscopic scale.

A superfluid rotates by forming an array of quantised vortices which carry the circulation and mediate angular momentum exchange between the superfluid neutrons and the normal component of the star, which is tracked by the electromagnetic emission. If vortices are strongly attracted, or 'pinned' to ions in the crust or flux tubes in the core of the star they cannot move out, and the superfluid cannot spin-down with the normal component, thus storing angular momentum. Sudden re-coupling of the components leads to rapid angular momentum exchange and a glitch [41]. Despite this qualitative picture having been developed early on, the exact nature of these events, the trigger mechanism and the exact nature of the pinning force are still a matter of debate after more than 40 years (see [42] for my recent review on the topic).

Together with collaborators in Milan I have carried out detailed microphysical calculations of the pinning force for realistic interactions and equations of state [43–45] and applied the results to calculations of the reservoir of angular momentum available to exchange during a glitch. In particular, comparing the theoretical reservoir to measurements of the activity of the Vela pulsar, can constrain nuclear physics parameters, such as the slope of the symmetry energy  $L$ , which plays a fundamental role in the crustal equation of state [46]. We have also shown how microscopic calculations of the pinning force can be combined with observations of the maximum glitch in a pulsar to measure its mass [47].

I also developed the first dynamical simulations that can track all phases of a giant glitch, from the rise to the relaxation [48], and used fits to Vela glitches to constrain Mutual Friction parameters. The same formalism was adapted to incorporate random unpinning [49] and model glitch size and waiting time distributions [50]. The coupling of vortex motion and large scale hydrodynamics also naturally leads to small glitches being much slower than fast glitches, and appearing not as sudden glitches, but more like timing noise, thus naturally explaining the cutoff at low glitch amplitudes that has been observed in the Crab pulsar [51]. With collaborators in Melbourne we have also developed two dimensional simulations of glitch relaxations, that include the effect of Ekman pumping on the dynamics [52].

I have also considered the viability of vortex avalanches as a trigger mechanism for pulsar glitches. Microphysical simulations of vortices in a spinning down container show that vortices can knock each-other on and give rise to glitches, with a size distribution that is compatible with a power-law, as in most pulsars (with only two pulsars, among which the Vela, that show evidence for a preferred size and waiting time for glitches [53]). However, due to numerical limitations, vortices are separated only by a few pinning sites in such simulations. I have shown that, close to the critical threshold for unpinning, vortices can skip many pinning sites and knock each-other on, even if separated by  $\approx 10^{10}$  pinning sites as in a realistic neutron stars [54]. I am currently developing two dimensional and three dimensional vortex lines simulations (work financed by my Sonata Bis grant and Marie-Curie fellowship) to study this scenario, and developing mean field approaches to include vortex knock on in large scale hydrodynamical simulations (Khomenko & Haskell, submitted).

### 6. Outstanding publications:

- Data from NASA ADS, 1st December 2017
- **100+ citations:**  
Haskell, B., Samuelsson, L., Glampedakis, K., Andersson, N., (2008), MNRAS 385, 531
- **50+ citations:**  
Haskell, B., Andersson, N., Jones, D.I., Samuelsson, L., (2007) Phys.Rev.Lett. 99, 231101  
Haskell, B., Jones, D.I., Andersson, N., (2006) MNRAS 373, 1423  
Haskell, B., Degenaar, N., Ho, W.C.G., (2012) MNRAS 424, 93  
Ho, W.C.G., Andersson, N., Haskell, B., (2011) Phys.Rev.Lett. 107, 101101  
Haskell, B., Cioffi R., Pannarale, F., Rezzolla, L., (2014), MNRAS 438, L71
- **Invited review articles:**  
Haskell, B. (2015), 'R-modes in neutron stars: Theory and observations', IJMPE 24, 1541007  
Haskell, B., Melatos. A., (2015) , 'Models of Pulsar Glitches', IJMPD 24, 1530008





7. *Publication summary:*

- Data from NASA ADS, 1st December 2017. Values in parenthesis refer to refereed publications only.
- Number of papers: 48 (39)
- Citations: 1014 (1005)
- Average citations: 21.1 (25.8)
- h-index: 21 (21)

8. *Grants obtained as principal investigator:*

- 2010-2012: Marie Curie IEF Fellowship, FP7: 'AMXP Dynamics', 252470, held at the 'Anton Pannekoek' astronomical institute, the University of Amsterdam, Amsterdam, the Netherlands
- 2013-2016: Australian Research Council DECRA fellowship, 'Modelling Superfluid Neutron Stars', DE13010108, held at the School of Physics, University of Melbourne, Parkville (VIC), Australia.
- 2016-now: Marie Curie Individual Fellowship (Reintegration), H2020: 'SuperDENSE', 702713, held at the Nicolaus Copernicus Astronomical Center, Warsaw, Poland
- 2016-now: NCN Sonata Bis: 'Superfluid neutron star dynamics', 2015/18/E/ST9/00577, held at the Nicolaus Copernicus Astronomical Center, Warsaw, Poland

9. *Research network activities:*

- since 2017: Vice-Chair and Managing Committee member for Poland of PHAROS, ESF-funded COST action CA16214
- 2014-2017: participating member of NewCompStar, ESF-funded COST action MP1304
- 2008-2013: participating member of the ESF funded research networking program COMPSTAR

10. *Refereeing:*

- **Referee for:** Monthly Notices of the Royal Astronomical Society, The Astrophysical Journal, Physical Review Letters, Physical Review D, Classical & Quantum Gravity, Astrophysics & Space Science, General Relativity and Gravitation, Europhysics Letters, European Physical Journal E.
- **Reviewer for:** Australian Research Council (ARC), Italian Ministry of Education & Research (MIUR), Chilean National Council for Research (CONICYT), European Science Foundation (ESF), Sabanci University (Turkey).

11. *Conference Organization:*

- 2017: NewCompStar Annual Meeting, 27-31 March 2017, Warsaw, Poland
- 2014: Orange Pulsar Meeting, 26-28 November 2014, Melbourne, Australia
- 2012: Magnetic Fields in Neutron Stars: origin, evolution and decay, 12-15 June 2012, Amsterdam, the Netherlands

12. *Conference Participation:*

**Invited Talks:**

- 2017, October: ECT\* Workshop, New Perspectives on Neutron Star Interiors, Trento, Italy
- 2017, September: IAU Symposium 337, 50 Years of Pulsars, Jodrell Bank, UK -Plenary talk
- 2017, June: EWASS 2017, Prague, Czech Republic
- 2016, April: The origin, equilibrium and evolution of magnetic fields in neutron stars, Alicante, Spain
- 2014, November: Orange Pulsar Meeting, Melbourne, Australia
- 2014, September: XI Quark Confinement and the Hadron Spectrum, St Petersburg, Russia
- 2014, April: St Cugat Forum in Astrophysics, St Cugat, Spain - Plenary Talk



- 2014, April: GGI Neutron Star Workshop, Florence, Italy - Graduate Lecture
- 2012, July: XIII Marcel Grossman Meeting, Stockholm, Sweden
- 2012, June: Magnetic Fields in Neutron Stars, Amsterdam, the Netherlands

#### Contributed Talks:

- 2016, October, WE Haereus Seminar: Neutron Stars, Bad Honnef, Germany
- 2016, July, GR21, New York City, USA
- 2015, December, 28th Texas Relativity Meeting, Geneva, Switzerland
- 2015, December, ACGRG Meeting, Melbourne, Australia
- 2015, June, NewCompStar Annual Meeting, Budapest, Hungary
- 2014, July, AAS Meeting, Sydney, Australia
- 2014, April, Problemi Attuali di Fisica Teorica, Vietri sul mare, Italy
- 2014, February, ANITA meeting, Sydney, Australia
- 2013, December, ACGRG7, Hamilton Island, Australia
- 2013, July, Neutron Stars: Nuclear Physics, GWs and Astronomy, Guildford, UK
- 2013, July, GR20 and Amaldi meeting, Warsaw, Poland
- 2013, May, NS2013 symposium, Amsterdam, the Netherlands
- 2012, April, Problemi Attuali di Fisica Teorica, Vietri sul mare, Italy
- 2012, January, First Dutch GW meeting, Amsterdam, the Netherlands
- 2011, July, Astrophysical Transients INT workshop, Seattle, USA
- 2011, May, Compstar Annual Meeting, Catania, Italy
- 2011, February, HTRS2011, Champerry, Switzerland
- 2010, February, Compstar Annual Meeting, Caen, France
- 2009, February, The crust of compact stars, Coimbra, Portugal
- 2008, June, ASTRONS workshop, Istanbul, Turkey
- 2008, February, NS dynamics workshop, Gregynog, UK
- 2007, July, GR18 and Amaldi meeting, Sydney, Australia
- 2006, April, Britgrav 6, Nottingham, UK - **best student talk prize**
- 2004, September, Britgrav 4, Oxford, UK
- 2004, July, GR17, Dublin, Ireland

#### 13. *Invited Seminars and Colloquia*

- 2017, November: NCAC Warsaw, Poland
- 2017, March: NCAC Torun, Poland
- 2017, February: Universita di Parma, Parma, Italy
- 2016, December: Observatoire de Paris Meudon, Paris, France
- 2016, November: Warsaw Technical University, Warsaw, Poland
- 2016, October: Universitat Autònoma, Barcelona, Spain
- 2016, March: Nicolaus Copernicus Astronomical Center, Warsaw, Poland
- 2016, June: Nicolaus Copernicus Astronomical Center, Warsaw, Poland
- 2016, March: Nicolaus Copernicus Astronomical Center, Warsaw, Poland
- 2015, August: University of Melbourne, Melbourne, Australia
- 2015, February: Monash University, Melbourne, Australia
- 2014, September: University of Western Australia, Perth, Australia



- 2014, September: Curtin University, Perth, Australia
- 2014, July: Sydney Institute for Astronomy, Sydney, Australia
- 2014, May: Victoria University, Wellington, New Zealand
- 2014, April: LENS, Florence, Italy
- 2013, September: University of Melbourne, Australia
- 2013, May: Tuebingen University, Germany
- 2013, March: AEI, Potsdam, Germany
- 2012, November: Universita di Milano, Milano, Italy
- 2012, February: ASTRON, Dwingeloo, The Netherlands
- 2011, November: West Virginia University, Morgantown, USA
- 2011, November: Washington University, St.Louis, USA
- 2011, November: Montana State University, Bozeman, USA
- 2011, June: Sterrenwacht Leiden, University of Leiden, Netherlands
- 2011, June: Argelander Institute, University of Bonn, Germany
- 2011, March: API, University of Amsterdam, Netherlands
- 2010, October: GRAPPA, University of Amsterdam, Netherlands
- 2009, November: INAF, Milano, Italy
- 2009, June: API, Amsterdam, Netherlands
- 2008, May: University of Southampton, UK
- 2007, September: Universita di Parma, Parma, Italy
- 2006, October: Queen Mary University, London, UK

14. *Membership of professional associations:*

- Since 2017: Polish Astronomical Society
- Since 2017: European Astronomical Society
- Since 2013: Austrasralasian Society for General Relativity and Gravitation

15. *Teaching Experience:*

- 2009-2016: Taught a section of the 'Relativistic Astrophysics' course of Prof. P.Pizzochero at the University of Milan, Italy
- 2010: Taught an ASTROVARIA masters course with Dr. A.Watts at the University of Amsterdam, the Netherlands
- 2008-2009: Taught a section of the course 'mathematics for electronic and electrical engineering' at the University of Southampton, UK
- 2007: Taught the full course 'complex variables and transforms' at the University of Southampton, UK

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