ICONS abstracts

Observations of long bursts
Khaled Alizai

Type-I X-ray bursts are caused by unstable thermonuclear burning of accreted matter on the surface of neutron star. A typical Type-I X-ray burst has a fast rise followed by a decay time of a couple of tens of seconds, and is thought to be He or He/H ignited bursts in a ~1m thick layer. This unstable burning produces carbon (C) and heavier elements, that sink deeper into the 'ocean' of the neutron star. Two rare sub-categories of type I X-ray bursts have durations from 10 min up to a whole day. About ~70 bursts of a duration of few tens of minutes have been detected, named intermediate long bursts, and they are most likely caused by an unusually thick He layer. A very rare type of X-ray bursts with duration of several hours are called superbursts. So far ~27 of these superbursts have been detected, and the current explanation for these events is an unstable burning of carbon in a deep layer (~100m). The ignition nature of these rare bursts make them interesting for probing the crust heat conduction properties of the Neutron stars. This has already been attempted by (Cumming, 2006), using a small sample of these events. In this presentation, I will give an overview of the current state of the search for these rare burst events, and present the preliminary results of the multi-observatory catalog, which is in preparation (Alizai et al.,2020?). At last I will show how the long duration bursts catalog can be used to improve the previous studies on the crust and interior of Neutron stars.

Low-level accretion processes during quiescence
Montserrat Armas Padilla

Neutron stars harboured in transient low mass X-ray binaries represent a fantastic window to study their crust properties, and thus, to provide insights into the high-density matter physics. In particular, to track the crustal cooling during the quiescent phase that follows an accretion episode provides key information on the thermal and superfluid properties of the neutron star interior. However, the definition of quiescence is gradually becoming ambiguous, as new studies show phenomenology which is most likely related to accretion processes when systems are observed at their lowest luminosities. Therefore, when inferring temperatures from spectral fits it is sometimes difficult to tell what is actually driving their evolution: accretion or the neutron star crust cooling processes.

In this talk, I will review the state-of-the art of low-level accretion processes onto neutron stars, with emphasis on identifying possible contamination by residual accretion during the quiescent phase.

Nuclear pasta simulations
Matt Caplan

Large scale simulations have been used extensively to study the structure, material properties, and phase diagrams of nuclear pasta. This talk will compare and contrast the two leading methods for simulating nuclear pasta: classical molecular dynamics and fully quantum mechanical Hartree-Fock calculations. I will also discuss recent work using classical molecular dynamics simulations to calculate the elastic properties of pasta, which find that it is the strongest known material in the universe.

Theory of nuclear surface burning
Yuri Cavecchi

Accreting neutron stars in low mass X-ray binaries show thermonuclear explosions on their surface known as Type I Bursts. The nature of the nuclear burning during the bursts depends on various factors, such as the accretion rate and heat flux from the lower layers. Also, the ashes left behind after the bursts will sink deeper into the neutron star and will eventually become part of the crust. I will review our theoretical understanding of the burning on the surface and its relation with the neutron star crust.

Crustal modes and X-ray bursts
Frank Chambers

High time resolution X-ray satellites provide an opportunity to observe oscillations in luminosity during particularly energetic events on neutron stars (NS). These oscillations may be explained by modes that exist in the interior and surface layers of these stars and could be used to probe the physics of these regions.

One interesting phenomenon that might result from modes on NSs are burst oscillations; high frequency modulations in the lightcurves of thermonuclear X-ray bursts on accreting NSs. The frequency of these oscillations can be offset from the NS spin frequency and can drift by several Hz. While most burst oscillations have been observed during H/He triggered bursts, there has been one observation of oscillations during a superburst on 4U-1636-536, which occurs deeper in the star as a result of unstable C burning. The frequency observed during this burst was more stable than those of the H/He bursts on the same star at ~582Hz.

In this talk I outline a mode model attempting to explain oscillations during this superburst. The model over-predicts the frequency drift by 90 % and does not match the predicted NS spin frequency inferred from H/He triggered burst oscillations and a similar mode model.

Recent developments in the modelling of neutron-star crusts.
Nicolas Chamel

The outer region of a neutron star consists of a solid crust, permeated by a neutron superfluid in its innermost part, possibly on top of a mantle of nuclear "pastas". During this talk, some of our recent developments in the modelling of neutron-star crusts in the framework of the nuclear-energy density functional theory will be presented.

Nuclear reactions in accreting neutron stars: neutron transfer reactions and detailed balance for fusion reactions in thermo-pycnonuclear regime.
Andrey Chugunov

The first and the main topic is neutron transfer reaction, which consists in quantum tunneling of weakly bounded neutron from one nucleus to another. To estimate the role of this process in nuclear evolution of crust of accreting neutron stars, I calculate the neutron transfer rate by averaging the transfer probability for fixed nuclei separation over realistic distribution of nuclei. I conclude that neutron transfer can modify reaction chains in accreting neutron stars and affect their heating and cooling. In particular, it can suppress cooling by URCA pairs of nuclei, which is supposed to be crucial for the hottest neutron stars. Then, I discuss the fusion reactions in thermo-pycnonuclear regime. Namely, I point out that under these conditions, strong plasma screening can affect the branching ratios for decay channels of compound nucleus, so one should consider this effect to get reaction network, which agrees with detailed balance principle and includes plasma screening effects properly.

Crust cooling of magnetars
Francesco Coti Zelati

Maximal cooling of neutron star crusts
Andrew Cumming

The luminosity of a neutron star at a given time after a transient event has a maximum value set by neutrino cooling. In this talk, I will present calculations of this maximal cooling curve and discuss the physics input that determines the luminosity as a function of time. I will then discuss the application of the maximal cooling curve to crust relaxation in magnetar outbursts. In some cases, observed luminosities can approach or exceed the maximum cooling curve, which has implications for the source distance, the angular size of the heated region, or microphysics calculations of neutrino emissivities in strong magnetic fields.

The physics of shallow heating
Andrew Cumming

The nature of shallow heating in accreting neutron stars is a major unsolved problem and source of uncertainty in fits of crust cooling models to observed cooling in quiescence. After a brief review of the different types of observational evidence for shallow heating, I will go through physical mechanisms that could act as a heat source at low density, including a low-density nuclear reaction, chemical separation at the ocean/crust boundary, and viscous heating associated with the accretion disk boundary layer. In each case, I will discuss what works and what doesn't in explaining the shallow heating inferred from fits to observed sources.

Crustal heating from nuclear reactions in accreting neutron-star crust
Anthea Francesca Fantina

X-ray observations of soft X-ray transients in quiescence suggest the existence of heat sources in the crust of accreted neutron stars. The heat is thought to be released by electroweak and nuclear processes triggered by the burying of ashes of X-ray bursts.

In this talk, the heating in the crust of accreting neutron stars from such nuclear reactions will be discussed. In particular, the importance of nuclear physics inputs and the impact of the details of the nuclear structure (e.g. shell effects) on the crustal heating will be assessed. Indeed, we will show that the evolution of an accreted matter element and therefore the location of heat sources are governed to a large extent by the existence of nuclear shell closures. The question of the shallow heat sources will also be briefly presented.

Observations of X-ray bursts
Duncan Galloway

Thermonuclear (type-I) X-ray bursts have long held promise as a probe of the thermal conditions in the neutron star crust. Confounding factors include the heat sources from accretion and stable burning prior to ignition, which may dominate the thermal conditions in the fuel layer. I will briefly describe the likely impact of the crustal conditions, and attempt to identify the optimal situation where the influence of the crust is maximal. Using a large sample of burst observations, the Multi-INstrument Burst ARchive (MINBAR), I report on a search for suitable observations, and will assess the possible impact of the crust conditions. Finally, I will discuss the prospects for future observations in improving the current observational situation.

Superfluidity in neutron star crusts
Vanessa Graber

Exhibiting extreme conditions that cannot be recreated on Earth, neutron stars provide an excellent environment to study the behaviour of ultra-dense matter. In particular, these compact objects are cold enough to host superfluid and superconducting phases - macroscopic frictionless quantum liquids - that impact the stellar dynamics. In this talk, I will focus on the superfluid component in the inner crust, providing an overview of our current understanding of this quantum condensate and its impact on macroscopic neutron star observables, specifically pulsar glitches.

Theoretical implications of thermal emission from quiescent NSs
Sophia Han

During the past 20 years, continued monitoring of neutron star cooling in transiently-accreting systems has been extensively performed using X-ray telescopes. Along with the development in theoretical models, these studies greatly enhanced our understanding of properties of dense matter that occurs in the neutron star interior. In this talk, I will briefly discuss what can be learned from the quiescent behavior of transients on inferring the equations of state, neutrino emission efficiency, crust composition, nucleonic superfluidity, and their uncertainties.

New models for Type I X-Ray Bursts and their ashes
Alexander Heger

We will present results from a grid of the next generation of models for Type I X-Ray bursts. These models include new nuclear physics input from JINA, better modelling of the accretion and surface layer, and a consistent substrate pre-heating from burning that avoids a lengthy "burn in" phase. In contrast to previous compilations that only varies accretion rate and assumes a fixed scaling of hydrogen mass fraction with metallicity, we also show variations in base heating, gravity, and independent hydrogen and metallicity scaling. In particular, we will show how these variations affect the ashes composition that goes into the crust.

Thermal emission from the full neutron star surface in a quiescent HMXB
Craig Heinke

We report the first clear detection of thermal emission from the full surface of a neutron star (NS) in a quiescent high-mass X-ray binary (HMXB), from Chandra and XMM-Newton observations of the Be/X-ray pulsar RX J0812.4-3114. Previously, thermal blackbody-like emission from a number of quiescent HMXBs has been identified, but always from a small area consistent with a polar hot spot, while these observations require a large emitting area consistent with the full NS surface. Comparison of the bolometric thermal luminosity, with the expectations from the outburst record for deep crustal heating, suggests the thermal luminosity is possibly slightly higher than expected. Our result proves that high-B-field NSs in quiescent HMXBs can show nearly uniform thermal emission, with implications for thermal conductivity in NS crusts and for studies of crust cooling in quiescent HMXBs.

Pulsar glitches and NICER monitoring of PSR J0537-6910
Wynn Ho

The spin rate of young pulsars can occasionally undergo sudden changes or glitches. Large glitches, like those seen in J0537-6910, provide unique insights into properties of the superfluid in the neutron star crust and possibly core. In some cases, they may even provide the means to measure the mass of the star, including those with no gravitational companion. Furthermore, in the case of J0537-6910, its spin and glitch behavior may be suggestive of emission of gravitational waves via r-mode oscillations. I report on timing analyses of ongoing NICER observations of PSR J0537-6910.

Crust reactions in connection with lab experiments
Zach Meisel

Nuclear reactions play a central role in observable phenomena from accreting neutron stars. X-ray bursts and phenomena accompanying the burial of surface-burning ashes involve thousands of nuclear reactions on hundreds of nuclei. A significant fraction of these can be constrained in the laboratory with direct and indirect experimental techniques, but the sheer number of reactions poses a daunting challenge. In this talk I will discuss how measurements are prioritized and provide examples of recent and ongoing experimental works that aim to reduce some of the most significant nuclear physics uncertainties for accreting neutron star observables.

The abundance and disorder of nuclear pasta in neutron star crusts
William Newton

We will show how the information extracted from GW170817 constrains the thickness, mass and moment of inertia of the neutron star crust. We will also present results from the most extensive set of 3D, microscopic quantum calculations of nuclear pasta to date, under conditions relevant to the crusts of neutron stars, and spanning the uncertainty in nuclear models. We show that quantum shell effects and the small differences in surface energies of different pasta configurations lead to a large number of local minima in their energy surfaces at a given density. The minima are separated by barriers of order 10keV. As the crust freezes, we estimate that pasta freezes into microscopic domains of order tens of lattice spacings or less, likely leading to an enhanced electrical and thermal resistivity from electron scattering on domain boundaries. We find pasta phases are predicted to occur at lower densities than typically estimated, around one-quarter nuclear saturation density, and that they initially they coexist with spherical nuclei. We show that it is a robust prediction that pasta accounts for around 70% of the crust mass and moment of inertia, and 25% of its thickness.

Simulating the thermal evolution of accretion-heated neutron stars
Laura Ootes

Accretion onto neutron stars in low-mass X-ray binaries pushes material of the crust to higher densities, which leads to a series of reactions at various depths in the crust. These reactions heat the crust of a neutron star out of thermal equilibrium with the core during an accretion outburst. When accretion halts, the crust relaxes back to an equilibrium state, which leads to observable crust cooling over periods 10^3-10^4 days. Comparing the observed cooling curves with simulations of the thermal evolution of accreting neutron stars can provide valuable insight in the crustal physics. In this review, I will discuss what has been learned from simulations of crust-cooling so far, how thermal evolution models have been progressed over the years and the progress to be made. Finally, I will discuss the open problems that still have to be solved.

Light and heavy clusters in warm stellar matter
Helena Pais

At densities below the nuclear saturation density and not too high temperatures ($T<20$ MeV), core-collapse supernova matter is unstable with respect to density fluctuations such that inhomogeneous structures develop and clusters can appear. Light (deuterons, tritons, helions, α-particles), and heavy (pasta phases) nuclei can be expected. Their appearance can modify the neutrino transport, which will have consequences in the dynamical evolution of supernovae and the cooling of proto-neutron stars. In this talk, light and heavy clusters are calculated for warm stellar matter in the framework of relativistic mean-field models, in the single-nucleus approximation. The clusters abundances are determined from the minimization of the free energy. In-medium effects of light cluster properties are included by introducing an explicit binding energy shift analytically calculated in the Thomas-Fermi approximation, and the coupling constants are fixed by imposing that the virial limit at low density is recovered. The resulting light cluster abundances come out to be in reasonable agreement with constraints at higher density coming from heavy ion collision data. Some comparisons with microscopic calculations are also shown.

An observational review of neutron star crust cooling in low-mass X-ray binaries
Aastha Parikh

Neutron stars in low-mass X-ray binaries have relatively low magnetic fields and can be used as laboratories to probe dense matter physics. The neutron star crust is interesting to study as the density in this crust increases by ~8 orders of magnitude over only ~1 km. In transient low-mass X-ray binaries, accretion outbursts can result in heating of the neutron star crust, causing the crust to thermally decouple from the core. Once such an outburst ceases, the crust begins to cool in order to reinstate the crust-core equilibrium. Monitoring this thermal evolution over time can allow us to probe the physical properties of successively deeper, denser layers of the crust. I will present an observational overview of our investigations into the dense matter physics in such crusts over the last ~18 years, carried out using the XMM-Newton, Chandra, and Swift observatories. I will discuss the various breakthroughs made, as well as the unsolved mysteries that such observational studies have presented us with, including results from our most recent observations which pose serious challenges to the crust cooling models.

Crust cooling emission from accretion-heated neutron stars in Be/X-ray transients
Alicia Rouco Escorial

In this talk I will summarise the current status in the field of the crust cooling emission for strongly magnetised neutron stars in Be/X-ray transients, and present the latest results of our studies about these systems. In particular, I will focus on the Be/X-ray transient 4U 0115+63, which exhibited a type-II outburst in 2015. During the low-luminosity state after the outburst, this source showed a slightly elevated emission above the detected quiescent level ('plateau phase'; Wijnands & Degenaar 2016; Rouco Escorial et al. 2017). The softness of the spectrum, the detection of pulsations, and its decay trend suggested that we likely observed the accretion-heated NS crust cooling going down slowly in time, similarly to what has been observed in the low-magnetic field neutron star systems. Interestingly, this system showed a new type- II outburst in 2017 that we monitored using Swift and XMM-Newton. For our surprise, we detected once again the 'plateau phase', meaning that this emission could be recurrent after outburst and the mechanism behind it might be the same. Finally, I will compare the behaviour of 4U 0115+63 with those observed for other two systems, V0332+53 and GRO J1750-27, and I will discuss the results in the context of the proposed models to explain the low-luminosity state in Be/X-ray binaries: accretion down to the magnetospheric boundary, low-level accretion onto the surface of strongly magnetised neutron stars and the heating/cooling scenario of these systems.

Neutron star crusts as viewed from nuclear experiments
Hendrik Schatz

Pairing, entrainment, and phonons in the inner crust
Michael Urban

In a recent study of pairing in neutron matter including screening effects [1], we found that the screening can actually turn into antiscreening with increasing density so that a sizable pairing gap can persist at all densities relevant for the inner crust. This finding supports the superfluid hydrodynamics approach to the entrainment problem [2], predicting a much weaker entrainment than the band-structure approach, with important consequences for glitches. The resulting large superfluid density enters also the effective theory describing the low-lying phonons in the crystalline and pasta phases of the inner crust [3]. The contribution of these phonons to the heat capacity will be discussed. References: [1] S. Ramanan and M. Urban, Phys. Rev. C 98, 024314 (2018); [2] N. Martin and M. Urban, Phys. Rev. C 94, 065801 (2016); [3] D. Durel and M. Urban, Phys. Rev. C 97, 065805 (2018).

Magneto-thermal evolution of neutron stars
Daniele Vigano

The evolution of magnetic and temperature in neutron stars has a direct imprint on their observed timing and spectral properties. The different manifestations of isolated neutron stars can be unified under an evolutionary scenario where the magnetic field plays a key role. X-ray data helps to study the physics of the neutron star crust, constraining in particular the microscopic properties of matter, like its resistivity. Moreover, latest results in 3D show the importance of the Hall instability in creating magnetic spots on one side, and the magnetospheric mechanism of triggering outburst on the other side.

Diffusive nuclear burning in cooling neutron stars
Marcella Wijngaarden

One of the challenges affecting the study of neutron star cooling is obtaining the interior temperature from observations of surface emission. The relation between surface temperature and interior temperature is set by the heat conducting properties of the thin outer envelope, which are highly sensitive to chemical composition. Most state-of-the-art cooling models consider the envelope to consist of chemically pure layers separated by narrow transition bands driven by diffusive mixing. However, diffusion can drive elements to depths where the density and temperature are sufficient to ignite nuclear burning, thus changing the composition and conductivity. We discuss the effect of diffusive nuclear burning in the envelope on the interpretation of observed neutron star cooling behaviour. Firstly, because diffusive nuclear burning can alter the chemical composition over time. Secondly, because for some compositions, diffusive nuclear burning in the envelope can produce a non-negligible heat flux for neutron stars in quiescence after accretion outbursts.

Accreted vs catalyzed crust: neutron star parameters
Julian Leszek Zdunik

The main parameters of a neutron stars and NS crust for the recently calculated models of accreted crust (BSk19-21 with proton shell effects) will be presented. The applicability of the approximate formulae for the crust thickness, moment of inertia of the crust and the differences between accreted and catalysed crust will be discussed. The presented formalism results in the difference between accreted and catalysed crust proportional to the total energy release due to the deep crustal heating.
