The X-ray mysteries of neutron stars and white dwarfs

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ABSTRACT BOOKLET

Oral Contributions and Posters

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Chapter 1

Invited Speakers

The highs and lows of transitional millisecond pulsars

M. Cristina Baglio[1]
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In this talk, I will provide a comprehensive overview of transitional millisecond pulsars from an observational perspective. These objects earn the label "transitional" due to their ability to switch back and forth between X-ray and radio pulsar states in a few days timescale, in response to variations of the rate of mass accretion. I'll delve into the multi-wavelength signatures observed during the X-ray state, enabling us to investigate distinct emission mechanisms active in this phase. Subsequently, I will present novel findings derived from observations of the prototypical transitional pulsar, PSR J1023+0038, emphasizing the recent discovery of pulsations in the optical band. Furthermore, I will explore the most recent model that attempts to explain the origin of the puzzling behaviour of these sources while in their X-ray state, shedding light on the latest advancements in this field and outlining the lingering questions that await resolution.

The strongest magnets of the Universe

Alice Borghese[1]
[1] *INAF-Osservatorio Astronomico di Roma*

Magnetars are the strongest magnets we know of. Their X-ray emission is powered by the instabilities and decay of their huge magnetic field ($\sim 10^{14}$–10^{15} G). The hallmark of these isolated neutron stars is the unpredictable and variable bursting activity observed in the X-/gamma ray regime and on different time scales (from milliseconds up to tens of seconds). These flaring episodes are often accompanied by enhancements of the persistent X-ray flux, which usually relaxes back to the quiescent level over months to years, the so-called outbursts. In this talk, I will review the observational properties of magnetars, showing a systematic analysis of outbursts and new results in the field. I will then finish with some considerations on magnetar-like activity from other classes of neutron stars and the possible evolutionary links between different neutron star families.

Magnetic White Dwarfs in X-rays

Ilaria Caiazzo[1,2]
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Only a fraction of white dwarfs are known to be magnetic, and their magnetic field strengths range several orders of magnitude, from a few Gauss (comparable to that of the Sun) to about a billion Gauss (similar to millisecond pulsars). The reason why only some white dwarfs appear magnetic and the origin of such diversity in field strengths are sill open questions in the field. Understanding such questions can shed light on the formation and evolution of magnetic fields in stars and their remnants, including neutron stars. Recently, a wealth of new observations, from radio to X-rays, have allowed to obtain more pieces of the puzzle. In my talk, I will present the current status of the field and present how new observations, especially from X-ray observatories, are pushing our understanding of magnetic white dwarfs forward.

White dwarf stars in the big data era

Maria Camisassa[1]
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White dwarf stars are the most common endpoint of stellar evolution. Therefore, these numerous, old and compact objects provide valuable information on the late stages of stellar evolution, the physics of dense plasma and the structure and evolution of our Galaxy. The ESA Gaia space mission has revolutionized this research field, providing parallaxes and multi-band photometry for nearly 360.000 white dwarfs. Furthermore, this data, combined with spectroscopical and spectropolarimetric observations, have provided new information on their chemical abundances and magnetic fields. This large data set has raised new questions on the nature of white dwarfs, demanding a thorough understanding of the physics that governs their evolution and a proper statistical analysis of their collective properties. In this talk, I will summarize these questions and I will describe possible explanations for them, on the basis of detailed theoretical models and population synthesis studies.

Neutron-star population synthesis: an overview and new results

Vanessa Graber[1]
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Although about a billion neutron stars exist in our Milky Way, observational constraints limit us to only observing a few thousand of these compact objects. Pulsar population synthesis bridges this gap by simulating synthetic populations of neutron stars and comparing these to the observed sample of pulsars to constrain uncertain neutron-star physics. In this talk, I will summarise the current state-of-the-art of radio pulsar population synthesis and explore the possibility of using simulation-based (also called likelihood-free) inference based on artificial neural networks to estimate the parameters governing the magnetic and rotational properties of isolated Galactic radio pulsars. For this purpose, I will discuss our newly developed population-synthesis software, which allows us to simulate the neutron stars' dynamical and magneto-rotational evolution as well as their radio emission and incorporate selection biases of typical radio surveys. We subsequently use this framework to generate an extensive database of synthetic pulsar populations to train and validate a mixture-density network to recover the posterior distribution of those parameters that govern the neutron stars' properties at birth. I will conclude by presenting our new inference results for the observed pulsar population.

Latest news and future prospects on measurements of neutron star masses and radii

Sebastien Guillot[1]
[1] *IRAP / CNRS*

More than 50 years after the discovery of neutrons stars, their interior composition and structure remain unknown. Because the extreme densities and matter asymmetry in neutron star interiors are out of reach for Earth laboratories, the equation of state of bulk nuclear matter is unknown, and its determination would have implication for astrophysics and nuclear physics. Thankfully, measurements of neutron stars masses and radii are direct probes of the interior of these compact objects, and therefore on the composition and behaviour of dense nuclear matter. Mass measurements have been accessible from radio pulsars in binary systems since the discovery of the Hulse-Taylor pulsar in the 1970s, providing exquisite precisions for neutron stars between 1.2 and 2.1 Msun. In the past two decades, XMM-Newton and other X-ray observatories have provided some measurements of neutron star radii, but with limited precision in comparison to the mass measurements. However, recently, observations with NICER resulted the most promising, robust and precise measurements. In this walk, I will give a quick historical overview of mass and radius measurements, followed by a presentation of the key and recent results from the NICER mission. The talk will finish with a discussion of expected constraints from future observatories.

Neutron star cooling

Craig Heinke[1]
[1] *University of Alberta, Edmonton, Canada*

Measuring the temperatures of neutron stars provides a valuable way to study the physics of their interiors, including possible insight into the composition of the core and the presence of superfluidity. I will summarize the theory of neutron star cooling (from an observer's perspective), and discuss several observational applications. I will outline the minimal cooling paradigm, possible enhanced cooling processes (such as direct Urca), Cooper-pair neutrino emission, and possible crust cooling processes. (I omit magneto-thermal evolution related to high magnetic fields.) Observational applications include the observed temperatures of young neutron stars; the cooling of accreting neutron stars in low-mass X-ray binaries after outbursts; the observed core temperatures of neutron star low-mass X-ray binaries in quiescence; and the controversial detection of a temperature decline of the Cas A neutron star.

Long period pulsars

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[2] *Institute of Space Sciences, Consejo Superior de Investigaciones Científicas*

Magnetars, which are highly magnetized, young neutron stars, are known for their sporadic periodic bursts of X-rays, gamma-rays, and radio waves, believed to be triggered by intense magnetic activity. As they evolve, their rotation rate slows, their magnetic fields decay, and both their radio and X-ray activity should cease. Some magnetars may be slowed by fall-back accretion to slow rotation rates, yielding high X-ray emission but not radio emission.

We have discovered new Galactic radio sources which repeat on long periods, from tens to hundreds of minutes. The emission is bright and highly linearly polarised, and strongly resembles that produced by pulsars and magnetars, yet with such slow periodicity, cannot be driven by spin-down. Could they be a form of ultra-long period magnetar, or are they something else, or are their multiple classes? I will describe the sources, including new discoveries, show our current thinking on the origin of their emission, and conclude with future survey plans across a range of telescopes.

Beyond Accretion Limits: the Rise Of pulsating Gems

GianLuca Israel[1], on behalf of a larger team[2]
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[2] *Planet Earth*

The discovery of several UltraLuminous X-ray sources (ULXs) exhibiting fast and rapidly evolving X-ray pulsations unequivocally associates these sources with accreting neutron stars orbiting relatively massive companion stars ($> 8M_{\odot}$). Among these ULXs, the brightest pulsating ULX (PULX), NGC5907 ULX-1, displays a source luminosity (a few 10^{41} erg s^{-1}) that exceeds its Eddington limit by 500-1000 times. These discoveries have raised several key questions, the most urgent of which include: what physical process (or processes) is driving the observed luminosities? What is the nature of compact objects in ULXs, and how can we definitively ascertain it? Why are PULXs so rare and elusive, and how can we identify more members of this class? In this presentation, I will provide a brief overview of the ULX class and then focus on PULXs, presenting the most recent results obtained for four PULXs: NGC5907 ULX-1, NGC7793 P13, M82 X-2, and M51 ULX-7. I will discuss how current-generation X-ray missions are already providing a wealth of information to address the aforementioned questions.

Recent Advances in the Modeling of Type I X-Ray Bursts and Nova Outbursts

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[2] *Institut d'Estudis Espacials de Catalunya, IEEC, Barcelona, Spain*

Most of the efforts undertaken in the modeling of XRBs have relied on non-rotating, 1D hydrodynamic simulations. Here, we present pioneering XRB models with rotation, computed with different angular velocities (up to 80% of the critical value) and discuss the differences obtained in the lightcurves and in the associated nucleosynthesis with respect to non-rotating models. We will also report our results of the coupling of a non-relativistic radiative wind model with a series of XRB hydrodynamic simulations, quantifying the expected contribution of XRBs to the Galactic abundances.

Classical novae (CNe) are a related class of thermonuclear explosions. We will report on new 2D/3D models of mixing at the core-envelope interface as well as 3D simulations on the interaction between the nova ejecta, the accretion disk and the secondary star. It is expected that part of the ejecta will mix with the outermost layers of the secondary. The resulting chemical contamination may have potential implications for the next nova cycle, once mass transfer resumes.

A current view of the population of non-recycled radio pulsars

Aris Karastergiou[1]
[1] *University of Oxford, UK*

The Thousand Pulsar Array programme has been running on the MeerKAT radio telescope since 2019, allowing us to examine a large, unbiased population of non-recycled pulsars. The data are collected with a single instrument, and processed in a uniform way, allowing us to draw conclusions on the population as a whole. The programme itself is aimed at addressing fundamental questions such as the pulsar birth rate and evolution of the physical processes in pulsars with time, through high-quality measurements of pulse profiles, spectra, and polarization. I will present the results of the programme so far, and the challenges they pose to the picture of a canonical pulsar. There is a great wealth of information in these datasets, with implications on the interpretation of data from specific objects of interest, including neutron stars with magnetar-like behaviour, ultra-long period pulsars, and Fast Radio Bursts.

The fascinating magnetic-field evolution of neutron stars: many questions, a few answers

Sam Lander[1]
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In a neutron star's crust, the coupled evolution of the magnetic field and the temperature are closely linked to high-energy phenomena we observe. The concerted efforts in numerical modelling, in particular over the last two decades, have brought this research field to maturity, where models can be directly confronted with observations. The first half of this talk reviews these achievements, and the aspects of neutron-star magnetic-field evolution that may now be regarded as qualitatively - even quantitatively - correct.

But beyond the scope of most current studies lies a range of exciting and far less well-understood phenomena. These include the elastic failure of the crust under high stress (which likely triggers magnetar bursts and flares), and magnetic-field evolution in the star's core (which may lead to late-time reactivation of magnetars, and affect the rotational evolution). Confronting these phenomena requires the inclusion of new pieces of physics: elasticity and plasticity theory, coupling with rotational evolution, and the superfluid and superconducting properties of the core. These are reviewed in the second half of the talk, inevitably concluding with more questions than answers.

An X-ray View of Fast Radio Bursts

Aaron B. Pearlman[1,2,3]
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[2] *Trottier Space Institute at McGill, Montreal, Canada*
[3] *California Institute of Technology, Pasadena, USA*

Fast radio bursts (FRBs) are extremely luminous radio bursts produced by unknown astrophysical objects located outside of our Milky Way galaxy. Although FRBs share phenomenological similarities with radio pulses observed from magnetars and other types of neutron stars, no electromagnetic radiation has yet been detected outside of the radio band from any extragalactic FRB source. The detection of an X-ray burst accompanying an FRB-like radio burst from the Galactic magnetar SGR 1935+2154 provided strong evidence for a magnetar origin for some fraction of the FRB population. It also suggests that magnetar-like high-energy bursts may be detectable from nearby FRB sources, making searches for multiwavelength counterparts from FRBs (particularly in the X-ray band) a promising avenue for advancing our understanding of the FRB phenomenon. In this talk, I will provide an overview of the current status of X-ray observations of FRBs, including new constraints from a sensitive, broadband simultaneous X-ray and radio observational campaign of the closest known extragalactic repeating FRB source, FRB 20200120E, which resides in a $\sim$10 Gyr-old globular cluster within the M81 galactic system. I will also discuss the prospects for detecting X-ray emission from nearby FRB sources, going forward, using current and next-generation X-ray telescopes.

Pulsars and propellers: X-ray and radio emission from the most mysterious white dwarf binaries

Ingrid Pelisoli[1]
[1] *University of Warwick, Coventry, UK*

X-ray and radio emission are commonly detected from accreting white dwarf stars in binary systems. In contrast, emission from non-accreting white dwarfs seems to be a very rare feature. Two types of white dwarf systems are known to show X-ray and radio emission in the absence of accretion: magnetic propellers and white dwarf pulsars. In both cases, the white dwarf has a close binary companion, but no transferred material reaches the white dwarf surface. Only two systems of each kind are known. In the magnetic propellers, AE Aquarii and LAMOST J024048.51+195226.9, mass is being transferred towards the white dwarf from the companion, but the material is then flung out by the white dwarf's magnetic field in synchrotron-emitting blobs. In the binary white dwarf pulsars, AR Scorpii and J191213.72-441045.1, both the spectral features and the observed light curves suggest an absence of steady accretion, but X-ray and radio emission are believed to be triggered by magnetic interaction between the white dwarf and its companion. In this talk, I will explain the observational properties of these systems and how different models have tried to explain the origin of emission, as well as the formation of these binaries.

Recent Results on Magnetic Cataclysmic Variables

Aarran Shaw[1]
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Cataclysmic variables (CVs) are interacting binaries in which a white dwarf is accreting matter from a (typically) main sequence companion. A common subclass of CVs are the so-called magnetic CVs, in which the white dwarf is highly magnetic, such that the accretion disk is disrupted and matter instead flows along the magnetic field lines on to the poles of the white dwarf. Though CVs, both magnetic and non-magnetic, have been well-studied for decades, they are still proving to be important for answering open questions about binary evolution, accretion physics and even cosmology. Here I will discuss some recent results regarding magnetic CVs, focusing in particular on recent efforts to characterize the mass distribution of their white dwarfs. I will also introduce the relatively recent discovery that many of these systems have a tendency to transition to unusual low-flux states, and detail ongoing studies which could shine a light on the changing accretion mechanisms at work.

Chapter 2

Radio pulsars and isolated neutron stars

A *NICER* View of the Nearest and Brightest Millisecond Pulsar: PSR J0437–4715

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Neutron stars provide a unique laboratory for probing the nature of ultra-dense matter in the universe. NICER, the Neutron Star Interior Composition Explorer is a NASA X-ray telescope aboard the International Space Station designed for Pulse Profile Modelling (PPM) of rotation-powered Millisecond Pulsars (MSPs). Leveraging NICER's megasecond exposures, large effective collecting area, and high time and energy resolution, PPM enables us to precisely measure the properties of these neutron stars, especially mass and radius, providing new insights into dense matter Equations of State (EoS). NICER has already successfully obtained radius constraints for two MSPs: PSR J0030+0451 and the massive pulsar PSR J0740+6620. On behalf of the NICER Science Working Group, in this talk, I will present our latest analysis on the nearest and brightest MSP, PSR J0437–4715, using the open-source software package X-PSI (X-ray Pulse Simulation and Inference; github.com/xpsi-group/xpsi). In combination with highly informative radio priors and advanced background modelling, for this 1.4 solar mass neutron star, we have inferred the tightest radius constraint obtained by NICER thus far. I will further discuss the implications of our findings for the neutron star EoS and the stellar magnetosphere.

Long-term Evolutionary Links Between the Isolated Neutron Star Populations

Ali Arda Gencali[1], Ünal Ertan[1]
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Using the fallback disc model, we have investigated the evolutionary connections between the isolated neutron star (NS) populations, namely ordinary radio pulsars (RPs), anomalous X-ray pulsars (AXPs), soft gamma repeaters (SGRs), dim isolated NSs (XDINs), high-magnetic-field RPs (HBRPs), central compact objects (CCOs), rotating radio transients (RRATs), and long-period pulsars (LPPs). Our results together with earlier work show that NSs evolving with fallback discs naturally yield different NS populations due to differences in their initial conditions (initial period, disc mass, and dipole moment). In the present work, our simulations indicate that: (1) A fraction of HBRPs evolve into AXP/SGRs, eventually becoming LPPs in their late phases of evolution. (2) Persistent AXP/SGRs appear to lack evolutionary links with CCOs, XDINs, and RRATs. (3) A fraction of RRATs, which have the highest estimated birth-rate, likely become XDINs. (4) Most RRATs pass through RP or HBRP phases early in their evolutions. Our results provide a quantitative support for the earlier ideas suggesting evolutionary connections between the NS families, especially RRATs, XDINs, and RPs, to explain the discrepancy between the estimated total birth rate of these NS populations and the core-collapse supernova rate, known as the birth-rate problem.

Fitting X-ray and gamma-ray spectra of all known high-energy pulsars with a synchro-curvature radiation model

Daniel Íñiguez-Pascual[1]
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Out of the total population of observed pulsars, a small percentage of them have been detected to emit non-thermal pulsed radiation in both X-rays and gamma-rays. Several relevant aspects of this high-energy emission, such as the emission mechanism producing it, are not well understood yet.

In this talk I will present an effective radiative model that addresses this problem, following the dynamics of accelerated charged particles in the outer magnetosphere of a pulsar and computing their emission via synchro-curvature radiation, with only three free effective parameters. Our formalism considers that the same population of particles is responsible for the emission at X-ray and gamma-ray energies. The theoretical model successfully adjusts the observational gamma-ray spectral data from the *Fermi*-LAT instrument of the whole population of gamma-ray pulsars. The model also resembles well the X-ray and gamma-ray bands of the Spectral Energy Distribution of a majority of the pulsars with data available in both bands, spanning up to eight orders of magnitude in energy. In addition, this formalism has been successfully used as a tool to detect for the first time non-thermal pulsed X-ray emission from known gamma-ray pulsars.

New thermally emitting isolated neutron stars from SRG/eROSITA

Jan Kurpas[1], Axel D. Schwope[1], Adriana M. Pires[1,2], Frank Haberl[3]
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[3] *Max-Planck-Institut für extraterrestrische Physik, Garching, Germany*

Famous for the cleanest thermal X-ray spectra of all isolated neutron stars (INSs), the class of X-ray dim isolated neutron stars (XDINSs) may potentially account for a significant fraction of the Galactic INS population. The study of their population properties, evolution and links to other INS families, however, is hampered by a very small sample size. The SRG/eROSITA All-Sky Survey is predestined to discover new XDINSs beyond the immediate solar vicinity. In this talk, we will present the search strategy to identify new XDINSs among the myriad of eROSITA sources, discuss the identified candidates that will form the foundation of a flux-limited sample down to 10^{-13} erg s^{-1} cm^{-2} (0.2-2.0 keV) and report on the results of a recent large XMM-Newton/VLT follow-up programme that led to the identification of several new thermally emitting INSs.

Vortex Avalanches and Collective Motion in Neutron Star Interiors

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Glitches in neutron stars result from angular momentum exchange between superfluid in the star's crust and the rest of the star. Most glitching stars exhibit a power law distribution of glitch sizes and exponential distribution of glitch waiting times, which can be explained in terms of avalanches of quantised vortices in the crust. In this presentation, we investigate the evolution of up to 600 vortices in a spinning-down container using a Gross-Pitaevskii model. For slow spin-down rates we observe a sequence of avalanches, each involving 20 vortices. We show that avalanches are triggered in regions where Magnus forces are largest. Each avalanche creates a region of low vorticity that propagates inward as vortices are redistributed in the crust. We present evidence of collective vortex motion both during and after each glitch. For faster spin-down rates we observe many overlapping mini-avalanches, which could be connected with timing noise.

Isolated neutron star candidates from 4XMM-DR9

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[2]*AIP*
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We report the results of XMM-Newton fulfil programs 088419, 090126, 092282, and 094311 to observe new thermally emitting isolated neutron star (INS) candidates from 4XMM-DR9 and 4XMM-DR12. With the goals to assess long-term variability and improve spectral determination and source localisation for follow-up studies, our program explores a more remote and better characterised INS population than that detectable in the full sensitivity of the eROSITA All-Sky Survey. The identification of these rare X-ray emitters relies heavily on probabilistic catalogue cross-matching and screening of suitable candidates; as such, it is a direct scientific validation of the catalogues, tools, and data products being delivered within the scope of the EU Horizon 2020 XMM2ATHENA project.

Modelling the non-thermal X-ray emission of pulsars from their multi-wavelength pulse profiles

Jérôme Petri[1]
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Since the launch of the Fermi gamma-ray telescope, several hundred radio-loud gamma-ray pulsars have been detected. Observing simultaneously their pulsed radio and gamma-ray emission helps to constrain the geometry and radiation mechanisms to localize the photon production sites. In this presentation we show how time-aligned gamma-ray light curve fitting of young and millisecond pulsars constrain their magnetospheric configuration, namely the magnetic axis and line-of-sight inclination angles. We find good agreement between our emission model and the time-aligned single- or double-peaked gamma-ray pulsar observations. We are currently extending our analysis to thermal and non-thermal X-ray emission using observations from several X-ray telescopes like NICER, RXTE, NuSTAR and XMM. Preliminary results applied to bright pulsars show that the non-thermal X-rays are produced between 20
For the first time it becomes possible to localize with high confidence the non-thermal X-ray emission sites within the magnetosphere.

The mystery of long-period pulsars

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The recent discovery of two radio sources, GLEAM-X J1627–52 and GPM J1839–10, with long periods of 18 and 21 minutes respectively, has animated debate about their nature. While their bright radio emission resembles radio-loud magnetars, their long periods challenge the neutron star explanation and standard spin-down mechanisms. On the other hand magnetic white dwarfs show longer spin periods, but dipolar radio emission from isolated magnetic white dwarfs has never been unambiguously observed. In this talk I explore potential explanations for these long-period sources. In particular, assuming a neutron star nature, I consider the possibility that such slow pulsars might be neutron stars with magnetar-like magnetic fields that have been spun down during an initial phase of fallback accretion from the supernova debris. However deep X-ray observations imposed limits on the X-ray luminosity of these two objects that challenge the magnetar interpretation. Furthermore population synthesis models seem to disfavor the existence of a population of long-period neutron stars with sufficient rotational-energy budget to explain the observations. On the other hand, due to their larger moment of inertia, a fraction of the population of magnetic white dwarfs may possess the rotational energies necessary to power the observed radio emission.

Nuclear pastas in neutron stars

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Up to 50% of the mass of the crust of a neutron star may consist of very exotic nuclear clusters with unusual shapes such as rods (spaghetti), slabs (lasagna), tubes (bucatini), and bubbles (Swiss cheese) collectively referred to as "nuclear pasta". Having quite different transport and mechanical properties compared to the rest of the crust, such a mantle could impact the magnetic-field evolution, the cooling of the star, oscillations, gravitational-wave emission, etc. However, the existence of nuclear pasta remains a matter of debate. We have revisited this issue in the microscopic framework of the nuclear energy-density functional theory using functionals accurately calibrated to both experimental and theoretical nuclear data. In particular, I will show how the inclusion of quantum shell effects can strongly influence the presence of pasta in neutron stars.

Chapter 3

Magnetars

Pulsed and Polarized X-ray Emission from Neutron Star Surfaces

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The intense magnetic fields of neutron stars naturally lead to strong anisotropy and polarization of radiation emanating from their surfaces, both being sensitive to the hot spot position on the surface. Accordingly, phase-resolved intensities and polarizations depend on the angle between the magnetic and spin axes and the observer's viewing direction. In this talk, we present results from a Monte Carlo simulation of neutron star atmospheres that uses a complex electric field vector formalism to treat polarized radiative transfer due to magnetic Thomson scattering. General relativistic and QED vacuum birefringence influences on the propagation of light from the stellar surface to a distant observer are taken into account. We outline a range of theoretical predictions for pulse profiles at different X-ray energies, focusing on magnetars and also neutron stars of lower magnetization. By comparing these models with observed intensity (XMM, Chandra and/or NICER) and polarization (IXPE) pulse profiles for select magnetars, and light curves for other isolated neutron stars, we obtain constraints on the stellar geometry angles and the size and location of the hot spots. For magnetars, we outline how polarization measures might inform us about the level of toroidal twist in the magnetospheric field.

Shallow heating in magnetars: role of electron captures

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The persistent thermal luminosity of magnetars and their outbursts suggest the existence of heat sources in their outer crust. The compression of matter accompanying the magnetic field decay may trigger electron captures. This scenario bears some resemblance to deep crustal heating in accreting neutron stars. The maximum heat released by each reaction and their locations have been calculated taking into account the Landau-Rabi quantization of electrons. Whereas the heat deposited is mainly determined by atomic masses, the locations of the sources are sensitive to the magnetic field strength, thus providing a new way of probing the magnetic fields of magnetars. Most sources are concentrated at densities $10^{10} - 10^{11}$ g/cm^3 with heat power $W^\infty \sim 10^{35} - 10^{36}$ erg/s, as found empirically by comparing cooling simulations with observations. The change of magnetic field required to trigger the reactions is consistent with the age of known magnetars. This suggests that electron captures may be a viable heating mechanism in magnetars [1]. Analytical formulas valid for arbitrary magnetic fields have been derived for the threshold density, pressure and maximum heat released [2]. Numerical results will be also presented.

[1] N. Chamel et al., Universe 2021, 7(6), 193.
[2] N. Chamel & A.F. Fantina, Universe 2022, 8(6), 328.

The 2022 reactivation of the magnetar SGRJ1935+2154

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SGR J1935+2154 is a galactic magnetar with a period P 3.25 s, discovered by Swift in July 2014 during an outburst event. This magnetar has shown significant activity, with flaring events occurring nearly every year since its discovery. The detection of intense burst activities in April 2020, along with its association with a fast radio burst (FRB 200428), has further strengthened the connection between magnetars and FRBs. In this talk, I will present the results of recent X-ray observations of SGR J1935+2154 using the XMM-Newton and NuSTAR telescopes. We studied the properties of both persistent and bursting X-ray emissions from SGR J1935+2154 during the initial weeks following its last outburst on 10 October 2022. We also performed a timing analysis, which revealed a period derivative that is three orders of magnitude larger than the value measured at the time of discovery. Furthermore, we also observed SGR J1935+2154 with three 2–32-m class radio telescopes to investigate FRB-like radio bursts and pulsed emission.

Investigating a Common Origin among some GRBs and FRBs

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We study a large sample of Gamma-ray Bursts and Fast Radio Bursts to investigate the possibility that some of them could be emitted by a common progenitor. By examining the temporal, spectral, and energetic properties, as well as their distributions and correlations, we find some candidates that could be consistent with a non-cataclysmic origin, such as a magnetar, and others that could be due to a cataclysmic origin such as the merger of two neutron stars. We discuss the implications of the results to the proposed models of FRBs and GRBs and constrain them when possible.

Is Polarisation the Key to Understanding Magnetar Emission? - Mode Conversion in a Magnetar Atmosphere

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Polarisation offers a unique opportunity to probe the physics in ultra-strong magnetic fields, including quantum electrodynamics (QED) effects which have not been experimentally validated before. Magnetars are the strongest magnets known in the present universe and an ideal target for polarimetric observations in the X-rays. To date, four magnetars have been observed by Imaging X-ray Polarimetry Explorer (IXPE), the first telescope dedicated to observing the sky in polarised X-rays. The interpretation of these observations requires new model atmospheres which account for the QED effects in the magnetised vacuum alongside the plasma. When the contributions of the two components in the dielectric tensor become equal, the so-called vacuum resonance appears, and mode conversion occurs. We computed plane-parallel atmosphere models under different conditions (magnetic field strength/orientation and temperature). Our results show that the inclusion of QED effects in the atmosphere, allowing for complete and partial mode conversion, significantly affects the spectro-polarimetric properties. Finally, we discuss the power of X-ray polarimetry to our understanding of magnetar behaviour, the observability of these polarisation features with polarimetric investigations and recent results for atmospheres with varying degrees of ionization and particle bombardment.

Numerical study of X-ray emission in the radiation-rich environment of magnetar magnetospheres

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Neutron star magnetospheres are a source of abundant X-ray activity. They have transients observed in different bands, like the fast radio burst (FRB) and associated hard X-ray flare from the Galactic magnetar SGR 1935+2154. We present global models for magnetar X-ray emission, including a landmark first-principle radiative particle-in-cell simulation of the twisted magnetar magnetosphere. In one scenario, plasma particles accelerated by surface-motion-induced discharges interact resonantly with thermal background photons. The up-scattered high-energy photons drive secondary pair production and ignite a magnetospheric circuit that persistently generates X-rays. We divulge the plasma properties of such a magnetospheric circuit, including densities and velocities, and give an outlook on alternative ignition scenarios for persistent magnetar X-ray emission. Plasma-filled magnetar magnetospheres with critically twisted magnetic fields can drive outbursts of hard X-rays and millisecond-duration FRBs. We discuss criteria for the instability of 3D twisted flux bundles in the force-free dipolar magnetospheres and compare their energetic properties to observations of magnetar X-ray flares.

INTEGRAL discovery and XMM-Newton follow-up observations of a magnetar giant flare in the starburst galaxy M82

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Giant flares, short explosive events releasing up to 10^{47} erg in gamma-rays in less than one second, are the most spectacular manifestation of magnetars. Their rate of occurrence is poorly constrained, as only three have been seen from three different magnetars in the Milky Way and in the LMC in half a century. This small sample can be enlarged by the discovery of extragalactic events, since for a fraction of a second giant flares are sufficiently bright to be visible up to distances of a few tens of Mpc. However, at these distances they are difficult to distinguish from regular short gamma-ray bursts (GRBs).

I report the discovery of GRB 231215A, positionally coincident with the starburst galaxy M82 and the deep limits on its X-ray and optical counterparts that we obtained within a few hours. These limits, as well as the lack of a coincident gravitational wave signal, unambiguously qualify this burst as a giant flare from a magnetar in M82. This is the first magnetar giant flare that has been rapidly identified and securely associated with a nearby galaxy, thanks to a precise localisation obtained in near real time with the INTEGRAL satellite.

INTEGRAL observations of magnetars

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The INTEGRAL satellite has collected a large amount of data on magnetars in our Galaxy, spanning more than 20 years starting from 2003. The large data set obtained with the IBIS/ISGRI instrument at energies above 20 keV allows us to study both the properties and long-term evolution of their persistent hard X-ray emission and the population characteristics of the short bursts emitted during active periods. We present the results of a comprehensive analysis of the detected magnetars exploiting the most recent calibrations and analysis software. These include the results of a sensitive search for magnetar bursts, which led to the collection of large burst samples for SGR 1806-20 and SGR J1935+2154.

Can a Magnetar Glitch Affect the X-ray Burst Properties?

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SGR 1935+2154 has exhibited frequent episodes of intense X-ray burst activities in recent years, some of which were accompanied by radio bursts. The source also experienced glitch events between October 2020 and October 2022. During this period, two major burst activities took place: one in September 2021 and another in January 2022 (starting December 2021 and continuing until February 2022). To investigate the potential effects of glitches on the burst properties, we studied the January 2022 and September 2021 activities and compared them to the burst history of the source since its discovery in 2014. The mean burst duration resembles previous activities, albeit shorter than that observed in 2020, coinciding with the emission of radio bursts. Additionally, the mean burst spectral properties indicate a softer spectrum compared to earlier episodes, indicating a long-term trend of softening since 2016, accompanied by increased burst fluence and blackbody emission radii. Analysis of the power-law indices of the $R^2_{BB} - kT_{BB}$ correlation reveals an evolving trend during 2019-2022, with the soft component exhibiting a steeper slope while the hard component shows a less steep trend.

Long-term study of the 2020 magnetar-like outburst of the young pulsar PSRJ1846-0258 in Kes 75

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Magnetar-like activity has been observed in a large variety of neutron stars. PSR J1846-0258 is a young 327 ms radio-quiet pulsar with a large rotational power ($\sim 8\times10^{36}$ erg s^{-1}), and resides at the center of the supernova remnant Kes 75. It is one of the rare examples of a high magnetic field pulsar showing characteristics both of magnetars and radio pulsars, and can thus provide important clues on the differences in the emission mechanisms between these two classes. On August 1st 2020, after nineteen years of quiescent stable emission, the source underwent a magnetar-like outburst, which was followed up with several observations by *NICER*, *XMM-Newton*, *NuSTAR* and *Swift*. In this work, we report on the long-term timing and X-ray spectral properties of the source following the 2020 outburst, and place upper limits on any radio activity. We demonstrate that the pulsed flux increased by a factor > 6 during the outburst, followed by non-trivial variability in the spin-down rate. In particular, we find hints for an oscillation in the frequency derivative with a timescale of 50-60 days, recovering later on to stable quiescence.

Detailed Phase-Resolved Spectroscopic and Spectro-polarimetric Analysis of Magnetar 1RXS J170849.0-400910 with XMM-Newton, NuSTAR, and IXPE

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Magnetars, a subclass of the isolated neutron star population, possess magnetic fields of up to 1.0×10^{15} Gauss − 1 to 3 orders of magnitude stronger than those of rotation-powered pulsars. The decay of these magnetic fields produce bright soft and hard X-ray emission. The ultra-strong magnetic fields induce highly polarized signals in the X-ray radiation. These spectro-polarimetric properties depend upon the geometry of the system, the surface temperature distribution, and the configuration of the emission from the condensates and atmosphere. Thus, by employing phase-resolved spectropolarimetry, the magnetar emission topology, magnetic-field line configuration, and surface characteristics can be explored.

1RXS J170849.0-400910, one of the brightest magnetars, exhibits one of the highest pulsed fractions among magnetars, enabling highly detailed phase-resolved spectroscopic analysis. In this presentation, I will share the results of a deep NuSTAR+XMM-Newton simultaneous observation which affords the most in-depth broadband X-ray phase-resolved spectroscopy of 1RXS J170849.0-400910 to date. The rich spectroscopic detail also informs several spectro-polarimetric insights from an IXPE observation of the source. I will highlight how this comprehensive broadband spectropolarimetry supports investigations into current theoretical models of magnetar X-ray radiative processes in highly magnetized regimes.

Chapter 4

Magnetic field evolution and neutron star cooling

Evidence of gapless neutron superfluidity from the late time cooling of transiently accreting neutron stars

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The current interpretation of the observed late time cooling of transiently accreting neutron stars in low-mass X-ray binaries during quiescence requires the suppression of neutron superfluidity in their crust at variance with recent ab initio many-body calculations of dense matter. Focusing on the two emblematic sources KS 1731-260 and MXB 1659-29, we show that their thermal evolution can be naturally explained by considering the existence of a neutron superflow driven by the pinning of quantized vortices. Under such circumstances, we find that the neutron superfluid can be in a gapless state in which the specific heat is dramatically increased compared to that in the classical BCS state assumed so far [1], thus delaying the thermal relaxation of the crust. We have performed neutron-star cooling simulations taking into account gapless superfluidity and we have obtained excellent fits to the data thus reconciling astrophysical observations with microscopic theories [2]. The imprint of gapless superfluidity on other observable phenomena will be briefly discussed.

[1] V. Allard, N. Chamel, Physical Review C 108, 015801 (2023)
[2] V. Allard, N. Chamel, submitted.

Advancements in Three-Dimensional Thermal Evolution Modeling of Isolated Neutron Stars with MATINS Code

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Understanding the thermal evolution of isolated neutron stars is essential for unraveling their internal dynamics and evolutionary pathways. In this presentation, I will introduce the thermal evolution module of MATINS (MAgneto-Thermal evolution of Isolated Neutron Stars), a novel three-dimensional magnetothermal code. MATINS integrates a realistic background structure and state-of-the-art microphysical calculations for conductivities, neutrino emissivities, heat capacity, and superfluid gap models. I will outline the methodology employed for solving thermal evolution equations and discuss the microphysical implementation crucial for accurate modeling. I will present simulations using magnetic fields of varying topologies to produce temperature maps of neutron star surfaces. Furthermore, I will discuss the integration of MATINS-derived temperature maps with ray-tracing techniques to obtain phase-resolved spectra and pulsed profiles observable by distant observers. Our study offers insights into the thermal behavior of isolated neutron stars and provides a valuable tool for comparing observed thermal luminosities and X-ray light curves with theoretical models.

Two-fluid simulations of ambipolar diffusion in neutron star cores

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The structure and evolution of the magnetic field in neutron stars is far from understood. These objects exhibit diverse magnetic field strengths, which seem to correlate with their age, suggesting magnetic field decay. Likely, the dominant process evolving the magnetic field in their core is ambipolar diffusion, i.e., the joint motion of the charged particles and the magnetic field relative to the neutrons. Due to the nature of this effect, accurate numerical simulations must take into consideration the independent motion of the different particle species in the core (i.e. neutrons, protons, and electrons, joined by other species at increasing densities). To correctly capture the magnetic field dynamics under this effect, at least two-fluid simulations (charged particles and neutrons) are desirable. However, obtaining the velocity of such species numerically can be quite challenging, and has not been extensively explored in the literature.

Here, we present a comparison of different numerical methods of obtaining the velocities of charged particles and neutrons in an isolated, axially symmetric neutron star, for given magnetic field configurations; and we present simulations of the long-term evolution of the magnetic field in the core of such star, under ambipolar diffusion.

Modelling magnetar outburst with magneto-thermal simulation

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Magnetar outbursts are one of the most noteworthy manifestations of magnetism in neutron stars (NSs). They are episodes in which the X-ray luminosity of a strongly magnetised NS swiftly rises by several orders of magnitude to then decay over the course of several months, showing a predominantly thermal spectrum. Due to their small emission radii, these events are interpreted as the cooling of a hot feature in the outer stellar layers and can thus be studied within the framework of NS magneto-thermal evolution. I will present new simulations of outbursts as consequence of rapid heat deposition in a NS crust performed with state-of-the-art numerical codes that have been adapted from the customary study of secular cooling to short-term and highly energetic phenomena. In particular, I will discuss how observable parameters can be affected by the conditions of the hosting source (e.g. mass, composition, magnetic field), as well as those of the heated region (e.g. size, depth, heating timespan). The comparison of the signatures associated with these conditions to observations can put constrains on the physics of NS crusts, and ultimately shed light on the mechanism causing outbursts which, although widely believed to be magnetic in nature, remains poorly understood.

Understanding the dynamics of neutron star magnetic field through 3D magneto-thermal simulations

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The long-term evolution of neutron stars' internal, strong magnetic fields necessitates specialized numerical modeling. The wide range of phenomena observed in neutron stars suggests a complex magnetic structure, highlighting the importance of three-dimensional simulations to better understand their properties. In this talk, I will briefly introduce MATINS, a new three-dimensional numerical code. MATINS employs a finite-volume scheme with the cubed-sphere coordinate system, specifically designed to simulate the magneto-thermal evolution within neutron stars' crusts. I will also share results from the first fully coupled three-dimensional magneto-thermal simulations that incorporate the most realistic background structures and microphysical ingredients to date. These simulations employ a complex initial magnetic field structure based on proto-neutron star dynamo simulations. Our findings indicate that the simulated surface dipolar component remains weak over time, challenging the explanation for the observed strong surface dipolar fields responsible for the dominant electromagnetic spin-down torque. Consequently, we investigated the inverse cascade phenomenon within the realistic crust of neutron stars, focusing on the roles of magnetic helicity, crustal geometry, and magnetic boundary conditions. These insights significantly advance our understanding of magnetic field dynamics within neutron stars and the formation of the surface dipolar magnetic field.

Low-B magnetars are produced as a result of Tayler-Spruit dynamo at proto-NS stage

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We model three-dimensional magneto-thermal evolution of neutron stars with crust-confined magnetic fields formed as a result of a Tayler-Spruit dynamo at the proto-neutron star stage. We solve magnetic induction and thermal diffusion equations for two cases with different equatorial symmetry: (1) hemispherical dynamo and (2) dipolar dynamo. We find that dipolar dynamo produces magnetic field configurations and surface thermal maps which are in multiple aspects similar to observational properties of low-B magnetars. Namely, the dipolar magnetic field $\approx 10^{12}$ G is suppressed in comparison to maximum internal magnetic fields reaching 10^{15} G. Decay of these crust-confined magnetic fields heat the crust releasing up to 8×10^{33} erg/s during the first 10 kyr while staying above 10^{33} erg/s for 300 kyr and produces a well-localised hot spot causing modulations in total X-ray flux. Strong internal magnetic fields stress and break the crust close to the hot region releasing energies up to 10^{40} ergs, which are typical for magnetar bursts and outbursts. We also observe the formation of small-scale strong magnetic fields which could be responsible for the formation of absorption lines in soft X-ray spectra.

Constraints on the dense matter equation of state from young and cold isolated neutron stars

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The quest to constrain the Equation of State of ultra-dense matter and thereby probe the behavior of matter inside neutron stars core is a core goal in modern astrophysics. A promising method involves investigating the long-term cooling of neutron stars, comparing theoretical predictions with various sources at different ages. However, limited observational data and uncertainties in source ages and distances have hindered this approach. In this talk, I will share results from an extensive study on dozens of thermally emitting isolated neutron stars. By re-analyzing XMM-Newton and Chandra data and taking advantage of updated ages and distances, we identified three sources with unexpectedly cold surface temperatures for their young ages. To investigate these anomalies, we conducted magneto-thermal simulations across diverse mass and initial magnetic field ranges, considering three different Equations of States. We found that the "minimal" cooling mode failed to explain the observations, regardless of mass or magnetic field, as validated by a machine learning classification method. The existence of these young cold neutron stars suggests that any dense matter EoS must be compatible with a fast neutrino cooling process at least in certain mass ranges, eliminating a significant portion of current EoS options according to recent meta-modelling analysis.

Magnetothermal evolution in the cores of adolescent neutron stars: The Grad–Shafranov equilibrium is never reached in the 'strong-coupling' regime

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At the very high temperatures inside recently formed neutron stars, the particles in the core are in the 'strong coupling regime', where the frequent collisional forces cause them to act as a single, stably stratified, and thus non-barotropic fluid. In this regime, axially symmetric hydromagnetic quasi-equilibrium states are possible, which are only constrained to have a vanishing azimuthal Lorentz force. In such equilibria, the particle species are not in chemical equilibrium, thus Urca reactions tend to restore chemical equilibrium. If the stars remained hot for a sufficiently long time, this evolution would eventually lead to a chemical equilibrium state, in which the fluid is barotropic and the magnetic field satisfies the non-linear Grad-Shafranov equation. During this talk, we will present the results of our last publication, where we achieved the first long-term magneto-thermal simulations in this regime. Our results indicate that the feedback from the magnetic evolution on the thermal evolution is always negligible. Thus, as the core passively cools, Urca reactions quickly become inefficient at restoring chemical equilibrium, so the magnetic field evolves very little, and the Grad–Shafranov state is not attained. Therefore, any substantial evolution of the core magnetic field must occur later, when ambipolar diffusion becomes relevant.

Electron MHD in magnetar crusts with Landau-quantized electrons

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The effect of Landau quantization of electrons on the transport properties of magnetars has been studied for decades, but the magnetization associated with quantization has not been fully examined. We will discuss numerical simulations of magnetar crusts using electron magnetohydrodynamics including Landau quantization-induced magnetization, which generates small-scale field structures that can be efficiently dissipated. The implications of this phenomenon on the magnetothermal evolution of magnetars, including on the magnetar heating problem– that magnetars are systematically hotter than other neutron stars– will be reviewed.

Contrasting neutron star heating mechanisms with Hubble Space Telescope observations

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Passively cooling neutron stars would reach very low surface temperatures $T\_s < 10^4$ K within $< 10^7$ yr. However, likely thermal UV emission has been detected in HST observations of 4 much older neutrons stars (2 "classical" and 2 millisecond pulsars), implying $T\_s \sim 10^5$ K.

We computed their evolution with different heating mechanisms, finding that the relevant ones are rotochemical heating and vortex creep. The former consists of non-equilibrium beta reactions induced by the continuous spin-down of the NS. If there are superfluid nucleons in its core, chemical energy is stored until a threshold is reached. Then, part of the energy is rapidly released, raising the temperature. If the protons in the core are superconducting, the magnetic flux is concentrated in quantized flux tubes. Outside the flux tube cores, protons are superconducting, while inside they remain non-superconducting, so reactions occur mostly inside. Vortex creep is the friction of the quantized neutron vortices moving through the NS crust.

We find that all the observations can be explained by rotochemical heating with superconducting protons and suitable internal magnetic fields, or by a combination of vortex creep and rotochemical heating with superfluid neutrons.

Chapter 5

Recycled and transitional pulsars

Orbitally modulating gamma-ray signals in redback pulsar binaries: insights into particle acceleration in the winds of millisecond pulsars

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Intra-binary shocks (IBS), caused by the interplay between a recycled pulsar and its low-mass companion, primarily emit nonthermal X-ray radiation. This X-ray emission exhibits modulation at the orbital period of the binary, featuring a simple power-law spectrum with a photon index of 1.2 and a distinctive double-peaked light curve. These characteristics are effectively explained by IBS models, where pulsar-wind electrons are accelerated at the shock through magnetic reconnection and flow along a paraboloidal shock surface. Observations by X-ray telescopes like XMM-Newton, Chandra, and NuSTAR have provided crucial information about these systems' parameters and hinted at the possibility of higher-energy emission from "spider" binaries beyond the GeV emissions originating from the pulsar magnetospheres. Indeed, recent Fermi-LAT observations have revealed orbitally modulated gamma-ray signals from several redback systems, posing an intriguing puzzle. Proposed mechanisms to explain this phenomenon include the inverse-Compton process, where blackbody photons interact with pulsar-wind electrons, and synchrotron radiation generated by pulsar-wind electrons penetrating the IBS and reaching the companion's magnetosphere. In this presentation, we will delve into our investigations of these proposed scenarios for generating orbitally modulated gamma-ray signals in redback systems, potentially indicating the acceleration of electrons to PeV energies within pulsar winds.

An Anti-Correlation Between the X-ray Luminosity and Optical Orbital Modulation of PSR J1023+0038

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We present an unexpected anti-correlation between the X-ray emission and optical modulation of the transitional millisecond pulsar PSR J1023+0038. Using 18 X-ray/b-band simultaneous XMM-Newton observations (717 ks in total) taken during the LMXB state of the pulsar, we find that a general trend that the amplitude of the b-band orbital modulation was smaller when the observed X-ray flux was higher in an observation. Depending on the analysis method, the statistical significance of the anti-correlation can be from 2.1σ (a p-value of 0.037) to 3.7σ (a p-value of 0.00030). It is a surprising result since X-ray emission is widely believed to be the heating source in these types of binaries. There are other candidates, such as gamma-ray/pulsar winds, that could be the real heating sources, and this anti-correlation likely indicates that the X-ray emission may not be the main heating source causing the optical modulation.

Snooping around transitional millisecond pulsars: can accretion- and rotation-powered states co-exist?

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The increasingly thrilling investigation of millisecond pulsars has recently overturned a long-standing paradigm. Traditionally, these pulsars are indeed thought to shine as rotation-powered radio and/or gamma-ray sources only after a Gyr-long, X-ray bright phase fueled by accretion of matter from a low-mass donor star. However, XMM-Newton's discovery of a transitional millisecond pulsar, IGR J18245-2452, defies this categorization by swinging between radio and X-ray states. This pivotal finding triggered an intense quest for similar systems, leading to the observation of state transitions in two additional sources. In this context, the recent discovery of coherent optical pulsations from the archetype of transitional millisecond pulsars hints at the persistence of a rotation-powered magnetospheric process even in the presence of an accretion disk. I will review recent X-ray/optical simultaneous observations of the prototype of transitional pulsars, PSR J1023+0038, aimed at refining our understanding of the emission mechanisms at play. Additionally, I will present preliminary results from the first high-time resolution multiwavelength campaign of the robust transitional millisecond pulsar candidate, 3FGL J1544.6-1125, highlighting its role in redefining the conventional boundaries between accretion and rotation-powered pulsars.

Spider luminosities and the invisible black widow

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Black widows and redbacks are compact binary millisecond pulsars in close orbits with low-mass companion stars. Measuring their distances is challenging, typically inferred indirectly through radio emission dispersion measure and precise modeling of free electron density in the line of sight. The estimated luminosities of these pulsars depend strongly on their distance, which affects estimates for emission region sizes, fluxes, and temperature. These parameters impact the physics of companion star irradiation and the relativistic intrabinary shocks resulting from the collision between the pulsar and companion star winds. In this presentation, I will discuss our studies on the distances to these pulsars using the latest parallax measurements, along with their implications for X-ray and optical luminosities. I will also delve into our extensive multi-wavelength observing campaign of a black widow PSR J1720-0534, which is placed at a mere 191 parsecs from us according to the latest electron density model of the Galaxy. Despite deep observations in the gamma-ray, optical, near-infrared, and X-ray bands, we found no significant source around its radio-timing position, leading us to dub the source as "the invisible black widow." I will discuss a possible solution to this non-detection involving modifying the Galactic electron density model.

A Multiwavelength Hunt for Transitional Millisecond Pulsar Candidates

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Three transitional millisecond pulsar (tMSPs) systems have been discovered, each of which has been seen to actively switch between a sub-luminous X-ray accretion disk state and a non-accreting radio pulsar state on timescales of days to years. These systems offer a useful probe of the complex interactions between accretion geometry, magnetic fields, and the radio pulsar mechanism relevant to more common millisecond pulsar binaries. A small number of additional candidate tMSPs have been identified via their phenomenological similarities to the known tMSPs in their disk state. I will discuss methods to expand this sample using large X-ray and optical surveys in order to better define and understand tMSPs as a class, and to enable the detection of additional transitions in the future.

Identification and characterisation of the gamma-ray counterpart of the transitional pulsar candidate CXOU J1109

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Transitional millisecond pulsars (tMSPs) represent a crucial link between binary pulsars in their rotation-powered and accretion-powered states. During their active X-ray state, the tMSPs are the only low-mass X-ray binary systems that are detected up to GeV energies using the Fermi Large Area Telescope (LAT). CXOU J110926.4-650224 is a newly discovered tMSP candidate in an active X-ray state located close to a faint gamma-ray source, listed in the latest release of the Fermi/LAT point-source catalogue as 4FGL J1110.3-6501.

Confirming the association between CXOU J110926.4-650224 and the Fermi source is a key step towards validating its classification as a tMSP.

In this study, we present an analysis of Fermi/LAT data collected from August 2008 to June 2023, for a total of about 15 years, aiming to achieve a more accurate localisation of the gamma-ray source, characterise its spectral properties, and investigate any potential time variability. By thoroughly reconstructing the gamma-ray background around the source, we obtain a new localisation that matches the position of the X-ray source at the 95% confidence level and a detection significance of around 5.6 sigma. This establishes a possible spatial association between the gamma-ray source and CXOU J110926.4-650224.

GRMHD simulations of the X-ray switching modes in transitional millisecond pulsars

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Radio millisecond pulsars (MSPs) are often considered as the evolutionary end point of neutron stars in low-mass X-ray binary systems, a possibility reinforced by the observation of transitional MSPs, i.e. systems switching between accretion-powered and radio pulsar states. Transitional MSPs exhibit frequent, rapid (10s) variations of their X-ray luminosity, by a factor of 5-10. Understanding the mechanism behind these so-called "X-ray switching modes" could allow for a deeper understanding of the evolutionary sequence of transitional MSPs.

Using 2D axisymmetric GRMHD simulations, Parfrey & Tchekhovskoy (2017) reported that the interaction between the pulsar's magnetosphere with the accretion flow gives rise to one of the four possible accretion regimes, including direct accretion, magnetically-channelled accretion and propeller regime. Interestingly, they found an "intermediate state" where the flow enters the light cylinder but is expelled on a regular basis. Hence, this mechanism is a natural candidate for the mode switching behavior.

We will present dedicated 2D and 3D GRMHD simulations, set for consistency with the well-studied PSR J1023+0038, to test this model. For this, we confront the simulations' data to the X-ray switchig mode properties available to date, such as the timescale, variability within the modes and asymmetries in the transitions.

Investigating the formation of cannibalistic millisecond pulsar binaries using detailed stellar evolution

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Compact binary millisecond pulsars (MSPs), with orbital periods <1day and pulsar spins <30ms, challenge our understanding of binary evolution. Using the stellar code MESA, and including detailed pulsar spin evolution, we investigate the formation of binary MSP sub-classes: black widows (BWs), redbacks (RBs), and huntsman spiders (orbital periods >1day and RB like donors). While a lower fraction (below 0.3) of accretion onto the pulsar (or pulsar accretion efficiency) can reproduce MSP spins above 3ms, we find that an efficiency of at least 0.7 is required to cover the entire MSP range down to 1.4ms, the lowest observed spin. Cannibalistic MSP formation depends on the interplay between recycling of the pulsar and pulsar wind irradiation. A weak pulsar wind is enough to reproduce all the observed BWs, even though the most compact BWs (for example, J1953+1844 with an orbital period of 53min) require no irradiation. We find that RB formation depends critically on strong ablation suffered by the pulsar companion, with either strong irradiation and an accretion efficiency of 0.7 or weak irradiation with fully conservative accretion being the least requirement. Most of our RB evolutionary tracks continue to the BW regime connecting the two proposed channels for cannibalistic MSP formation.

X-ray pulsations from neutron star low-mass X-ray binaries

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We have investigated whether the absence of X-ray pulsations from the majority of neutron star (NS) low-mass X-ray binaries (LMXBs) could be explained by the extension of their inner disc radius to the NS surface. For the calculation of the inner disc radius, r_{in} we employed the recently developed analytical model that can account for torque reversals of LMXBs. In the model, r_{in} depends on the spin period as well as the dipole moment and the mass inflow rate of the disc. The results of our model indicate the mass accretion rates for most LMXBs are higher than the minimum critical rate at which the inner disc touches the NS surface, and thus impedes the pulsed X-ray emission. For the same model parameters, the model remains consistent with the observed pulsed X-ray luminosity ranges of accreting millisecond X-ray pulsars (AMXPs). For most sources, there is a critical period such that X-ray pulsations are allowed when the NS is spun up to periods below this critical level. Some sources with relatively weak dipole fields and/or sufficiently long periods could show non-pulsating X-ray emission for large ranges of X-ray luminosity variation.

Optical companions to binary MSPs in globular clusters

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The dense stellar environments of globular clusters make them the main factories of exotic compact objects. Among the several interesting classes of such systems, binary millisecond pulsars (MSPs) stand out as the most variegated. In fact, MSPs are rapidly spinning neutron stars formed in binary systems by mass accretion from an evolving companion star. However, the dynamic interactions within collisional environments can further perturb them, producing a wealth of exotic systems not predicted by standard evolutionary models.

A review of the state of the art of optical companions to binary MSPs in globular clusters is here presented. So far, about 18 companions to binary MSPs are certainly known. In particular, I will describe their main optical properties (color-magnitude diagram locations and light curve shapes) in the context of different classes (e.g. spiders, transitional MSPs, etc. . .) of binary MSPs. I will complement the scenario by presenting some new detections and discussing how X-ray observations have been fundamental in these studies. I will also discuss how optical non-detections of the companion can also be crucial, as in the case of NGC1851E (Barr+24,Science,383,275), a binary system hosting an MSP gravitationally bound to either a supermassive neutron star or a light stellar black hole.

Spying on the quickly variable optical sky: the enigmatic case of millisecond pulsars

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Millisecond pulsars (MSPs) are prime targets to study the interaction between a fast-rotating magnetic field and the in-falling plasma. Either the field rotation or accretion of matter is commonly assumed to power their electromagnetic emission.

The fast photometer SiFAP2 at the Galileo Telescope has recently observed optical pulses from two MSPs surrounded by an accretion disk. However, pulsations observed in the optical (and later in the UV by HST) are likely related to the acceleration of particles by the pulsar magnetosphere. Hardly fitting in the standard paradigm, these findings demand unconventional solutions. The stunningly high efficiency of these MSPs in producing optical/UV pulses and the X-ray properties observed by XMM-Newton and NICER, suggest that pulsations originate at the shock between the pulsar wind and the plasma. This would imply the coexistence of accretion and particle acceleration, thus requiring a revision of the conventional models of MSPs.

Thanks to the very high throughput of optical facilities, fast optical astronomy can open a new window also on radio MSPs and bright low mass X-ray binaries. I will present the first results of an exploratory high time resolution study of pulsars in different states performed in the optical, UV and X-ray band.

It's Getting Hotter: PSR J1622-0315 and Its Variable Asymmetries.

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PSR J1622-0315, one of the most compact redback binary MSPs discovered, shows extremely low irradiation of the companion despite its short orbital period. We model this system to determine the binary parameter values, combining optical observations from NTT in 2017 and NOT in 2022 with the binary modeling software ICARUS. We find a best fit neutron star mass of $2.2 \pm 0.6 M_{\odot}$, with a companion of $0.14 \pm 0.04 M_{\odot}$. We observe for the first time a subtle increase in irradiation over five years. While the irradiating luminosity in 2017 was 4.0E30 erg/s (three orders of magnitude lower than the pulsar spin down luminosity), we find that this irradiation luminosity has increased by almost 10-fold over five years. The asymmetric light curves exhibit lower than expected flux at phase 0.6 in 2017 and additional flux at phases 0.4 in 2017 and 0.75 (pulsar ascending node) in 2022. Using star spot models, we find better fits than those from symmetric direct heating models, with consistent orbital parameters. In summary, we find that PSR J1622-0315 combines low yet variable pulsar wind irradiation with asymmetric heating, and a relatively high neutron star mass.

The power of the dark side: hunting spiders to find the most massive neutron stars

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Compact binary millisecond pulsars, or 'spiders', consist of rapidly-spinning neutron stars spun up by a sustained accretion phase. As such, they are predicted to harbour the most massive neutron stars. These super-massive compact objects are paramount to finding the maximum neutron star mass, which has profound consequences for gravitational wave astronomy, nuclear physics, and stellar astrophysics.

Using the largest ground-based telescopes and phase-resolved spectroscopy, we study the optical counterparts of these cannibalistic systems, in which the pulsar ablates its companion with intense relativistic winds. This can produce strong irradiation effects that we can leverage by sampling different temperature-dependent absorption line species across the face of the companion. This in turn allows us to follow the temperature variation of the companion throughout its orbit and obtain a precise orbital solution.

Following the success of applying this technique to PSR J2215+5135 in 2018, we have continued to apply this analysis to three other systems, constraining companion temperatures throughout their orbits using only spectral features. We have also uncovered unique features, such as phase-dependent variations in absorption line strengths and evidence of asymmetric heating effects.

The radius of a millisecond pulsar from its surface far-UV and soft X-rays emissions.

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We present all the steps leading to new estimations of the radius of the millisecond pulsar (MSP) PSR J0437-4715 from far-UV and soft X-rays surface emissions, based on the work of González-Caniulef et al. (2019). After selecting and fitting calibrated data from the HST and ROSAT observations, we modelled the broadband spectrum of this MSP to account for the emission of the polar caps, and the rest of the surface using neutron star atmosphere models. A Markov-Chain Monte Carlo sampler has been used to infer the parameters, using the latest priors on the mass and distance of the MSP obtained from radio timing, and the latest prior on the extinction due to the interstellar medium obtained from one of the latest 3D maps of the Galactic dust distribution. This analysis has been performed for different atmospheric composition, confirming the original conclusion that the MSP is likely covered by a hydrogen atmosphere. We also obtained an updated, more reliable, radius measurement for PSR J0437-4715.

Quantifying the irradiation and expanding the population of spider pulsars

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Compact binary millisecond pulsars are systems in which the pulsar's relativistic wind can strongly irradiate and ablate their companion star. These spiders represent a unique environment to find super-massive neutron stars and to study the pulsar wind close to its origin, where it forms an intrabinary shock with the companion wind producing X-ray emission.

In this presentation I will show our multi-band optical light curves of PSR J1622-0315, one of the most compact known redbacks. The light curves indicate that the irradiation of the star's inner face by the pulsar wind is missing despite its short orbital period. These unexpected results, as well as the presence or absence of irradiation in the full spider population, can be interpreted by taking into account the ratio of pulsar wind flux hitting the companion star over its intrinsic flux.

Expanding the known spider population (74 systems) represents the key to identify the most massive neutron stars. In this regard, I will present the discovery of four redback candidates showing optical variable counterparts, which we found surveying pulsar-like Fermi unidentified sources. We also identify an hard X-ray source from the XMM-Newton catalog overlapping one of our candidates, which consolidates its spider identification.

Chapter 6

Accretion on compact objects: neutron star and white dwarfs

Variable structures in the stellar wind of the HMXB Vela X-1

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Unlocking the secrets of stellar winds in accreting X-ray binaries is crucial for understanding stellar evolution. Our study focuses on Vela X-1, offering a unique window into accretion processes due to its inherent variability and inhomogeneous wind. We employ long-term X-ray monitoring MAXI data to explore absorption fluctuations traced by hardness ratios over binary orbits in the 2–10 keV energy band, revealing insights into the wind structure. Our findings highlight the complex nature of the source, characteristic of an inhomogeneous environment, where the overdensities arise from the line-driven instability triggered in the stellar wind near the photosphere. By assessing orbit-to-orbit absorption variability, substantial deviations from the hardness mean profile are evident, and no discernible periodicity or other regular patterns are identified in the obtained hardness profiles. Furthermore, continuous monitoring of a neutron star's spin period reveals fluctuations over decades, believed to be influenced by accretion-induced torques. We explore whether the neutron star tends to spin up more during periods with higher X-ray hardness ratios. Our work establishes a method applicable to similar sources and future, more sensitive X-ray observations such as Einstein Probe.

Constraining the neutron star mass and moment of inertia from QPO triplets observed in 4U 1728-34 from the AstroSat/LAXPC observation

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We report the detection of three simultaneous quasi-periodic oscillations (QPOs) at ~ 40 Hz, ~ 800 Hz, and ~ 1100 Hz, along with a broad feature at ~ 150 Hz from the AstroSat-LAXPC observation of NS-LMXB 4U 1728-34. We obtain thirteen sets of QPO triplets in time-resolved power density spectra (PDS) for a particular observation, and these QPO triplet frequencies are found to evolve with time, showing a remarkable correlation with each other. Using the relativistic precession model (RPM), in which low-frequency QPO and lower kHz QPO frequencies are identified as twice the nodal precession and periastron precession frequencies, respectively, and upper kHz QPO frequency as orbital frequency, we determine a well-constrained mass and moment of inertia of the neutron star to be $M^*_\odot = 1.92 \pm 0.01$ and $I_{45}/M^*_\odot = 1.07 \pm 0.01$, respectively. We also numerically compute the moment of inertia of a neutron star spinning at 300 Hz for ten different equations of state by solving the Tolman-Oppenheimer-Volkoff (TOV) equation in a slow rotation approximation, and we find that the predicted values of neutron star parameters from QPO triplets favor stiffer equations of state.

The first simultaneous Xray/UV timing study of the accreting millisecond pulsar SAX J1808.4-3658

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SAX J1808.4-3658 is the prototype of accreting millisecond X-ray pulsars (AMXPs) and the first of this class to also show optical/UV pulsations during a bright accretion event. Before returning to quiescence at the end of its accretion outbursts this source shows several reflares of particular interest to provide insights into the physics of the accretion disk under low accretion rates. I will present the first simultaneous X-ray/UV timing study of XMM-Newton and Hubble Space Telescope observations of the source during the final stage of its 2022 outburst, focusing on the final flaring phase. Using XMM-Newton data we find shifts in the pulse phase and amplitude, with a distinct jump of approximately 0.4 in phase. The continuous coverage of XMM-Newton allowed unprecedented monitoring of this phenomenon. These phase shifts are among the most intriguing ever observed from this source and tightly correlate with the X-ray flux. We interpret such a correlation in terms of hot-spot drift on the neutron star surface, driven by variations in the mass accretion rate. I will also discuss the multi-band study in X-ray and ultraviolet bands aimed at investigating the physical mechanisms driving the latter phenomenon.

Accretion onto weakly magnetized neutron stars: theory and its application to X-ray burster GX 13+1

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Observations show that the X-ray emission of the accreting weakly magnetized neutron stars is polarized. The polarization degree of the observed sources exceeds the expectations derived from the previous models of these sources. In this talk, I introduce a new theoretical model, where we assume the emission of the accreting neutron star coming from the spreading layer, the extension of the boundary between the disk and the neutron star surface onto the surface. We then calculate the Stokes parameters of the emission accounting for relativistic aberration and gravitational light bending in the Schwarzschild metric. I present the main results of our simulations. I show how our results provide new insights into the X-ray polarization from weakly magnetized neutron stars observed with the Imaging X-ray Polarimetry Explorer (IXPE). I specifically focus on the X-ray burster GX 13+1 we observed in October 2023 with IXPE and the X-ray Multi-Mirror Mission Newton (XMM–Newton).

Supergiant Fast X-ray Transients

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Supergiant Fast X-ray Transients (SFXTs) are a sub-class of supergiant high mass X-ray binaries hosting neutron star accretor and displaying a unique variability in the X-ray domain, achieving a dynamic range up to 1e6 in a time scale of few ks. The origin of this variability is still actively debated and poorly understood. In this talk, I will provide a brief overview of the research status on SFXTs, as well as a summary of the most recent results obtained from our group exploiting observational campaigns performed with XMM-Newton, Swift, and NuSTAR.

New Accreting White Dwarfs Determined from X-ray Observations

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X-rays provide a unique fingerprint of accretion onto compact objects. We have recently made the first direct detection of planetary material accreting onto a white dwarf using X-ray observations with Chandra. This discovery confirmed G29−38 – the prototype of all metal-polluted white dwarfs with detected debris disks – as a significant source of soft X-rays. Our detection provided the first direct evidence of ongoing accretion of planetary material onto a white dwarf and allowed the first independent constraint on the accretion rate at such a system, finding an instantaneous accretion rate consistent with modeling of observed photospheric abundances. I will present this system along with recent results from an ongoing search for more isolated white dwarfs with soft X-ray emission, including a new metal-polluted white dwarf and two low-state, long-period period-bounce polars. From an evolutionary perspective, these new polars – both with 2-hour periods and cool sub-stellar companions – are particularly interesting since angular momentum loss driven only by gravitational wave emission may not be sufficient to explain their evolution to such long periods, perhaps requiring additional angular momentum loss mechanisms such as residual magnetic braking.

The puzzling X-ray binary MAXI J1810-222

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The X-ray transient MAXI J1810-222 was discovered in 2018 and has been active ever since. A long, combined radio and X-ray monitoring campaign was performed with ATCA and Swift, respectively. Despite being initially identified as a black hole candidate, the highly unusual outburst behaviour and the absence of information regarding the distance or the donor leaves the nature of the compact object open to ongoing debate. We detected a strong spectral absorption feature at about 1 keV with NICER which was described with a physical photoionization model. Through a deep scan of the parameters space, we found evidence for a spectral-state dependent outflow, with mildly relativistic speeds at 0.05-0.15 c. This finding would make MAXI J1810-222 the first X-ray binary where ultra-fast outflows have been detected at such high speeds. This is unlikely from classical thermal winds in Galactic X-ray binary and must involve either strong radiation or (most likely) a magnetically-driven wind. Motivated by this finding, we obtained a high quality XMM-Newton observation in 2023, in order to deeply investigate the nature of this absorption feature. The exact launching mechanism would discriminate a BH from a NS compact object nature. We will present preliminary results of this observation.

Weakly magnetized accreting neutron stars as seen by IXPE

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The Imaging X-ray Polarimetry Explorer, recently awarded by the American Astronomical Society with the Bruno Rossi prize, observed several accreting neutron stars in X-ray binaries during the first two years. Results obtained for weakly magnetized neutron stars allow us to model the geometry and the physical status of the different emitting regions (accretion disk, boundary/spreading layer) in a completely novel way, showing a more intricate scenario with respect to the one initially anticipated based on theoretical models. Particularly, the polarization measurements have demonstrated variations with energy and time, which are highly intriguing. Here, I present a summary of the IXPE findings for some of these sources, in particular 4U 1820-303, and Cir X-1.

Unveiling stellar wind structures in high-mass X-ray binaries: A high-resolution study of Vela X-1 with XMM-Newton

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The spectral and timing behaviour of high-mass X-ray binaries (HMXBs) offers a unique opportunity for the investigation of accretion onto compact objects and of wind structure in massive stars, two areas of research that are of utmost importance for today's and future astrophysics as can be seen from the prominence of these topics in the science cases for Athena. The bright and persistent HMXB Vela X-1 is one of the key systems for such studies. It has a complex and highly structured stellar wind that we analysed during a 100-ks XMM-Newton observation taken when the neutron star is in inferior conjunction. The low-energy coverage enabled by XMM-Newton gives us access to a plethora of emission lines. Building on our model and continuum results from our previous NuSTAR analysis, we are able to trace the onset of the wakes for the first time with high-time resolution, down to one pulse of the neutron star (283 sec). We also probe the presence of highly ionised atoms in the plasma originating from different locations in the stellar wind together with near-neutral ions thus indicating changes in temperature of the plasma.

Pulse Profile Modeling of the Accreting Millisecond X-ray Pulsar SAX J1808.4-3658

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Pulse profile modeling (PPM) is a technique to recover neutron star (NS) properties, such as compactness and hot surface features, from phase and energy resolved millisecond X-ray pulsar (MXP) data. PPM has been used by the NICER collaboration to constrain mass and radius of two rotation-powered MXPs to ~10 percent (Riley et al. 2019, 2021). In comparison, accretion-powered MXPs contain additional complexities such as an accretion disk and column which require additional model components, complicate PPM, and raise the computational cost. In this work, we study SAX J1808.4-3658, the first discovered accretion-powered MXP (Wijnands & Van der Klis 1998). We implement an accretion heated NS atmosphere (Bobrikova et al. 2023) and accretion disk background component. Based on NICER X-ray data from the 2019 outburst, we produce a synthesised data set on which we perform PPM, to test feasibility of Bayesian parameter recovery and model comparison.

Torque reversals of neutron stars in low-mass X-ray binaries

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We have developed an analytical model to estimate the inner disc radius and the torques acting on the neutron stars in low-mass X-ray binaries (LMXBs) in different rotational phases, namely the strong-propeller (SP), weak-propeller WP (accretion with spin-down) and spin-up (SU) phases together with the critical conditions for the SP/WP transitions, and the torque reversals of LMXBs. The model can account for some long-lasting problems of LMXBs for the conventional models: (1) accretion onto the neutron star at low X-ray luminosities and the transition to the SP phase (no accretion) at critical accretion rates much lower than the rates required for the torque reversals, (2) ongoing spin-down regime for a large range of accretion rates, and (3) torque reversals with comparable torque magnitudes on either side of the reversal, without substantial changes in the mass-flow rate. We will present the applications of this model to the WP/SP transitions of the transitional millisecond pulsars (tMSPs) and the observed torque reversals of 4U 1626–67, the best system to study the disk-magnetosphere interaction in LMXBs without a significant wind effect.

Pulse profile diagnostics in magnetized neutron-star X-ray binaries

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The general picture of X-ray emission from accreting X-ray binaries is well established. However, the complexity of the pulse profiles is a challenge for any detailed model.

We developed a standardized and versatile method to obtain optimally spaced energy-dependent pulse profiles of neutron-star X-ray binaries and we plan apply it to the full sample of sources which present a cyclotron line and have been observed by NuSTAR.

In this presentation, we will focus on a sample of prototypical sources and discuss several reduced quantities such as the puled fraction, aka the fractional variability as function of energy, the amplitude and phase of the first harmonics, and the self correlation/lag spectrum. Among others we will show the cases of Cen X-3, Her X-1, and 4U 0115+63.

We show quantitatively that there are generally two regions with different trends for the pulsed fraction, below and above 10-15 keV, that at an energy corresponding to the iron line or the cyclotron scattering feature, there are dips or excesses in the pulsed fraction.

Even if the extreme heterogeneity of pulse profiles poses a challenge, the comparison of individual cases obtained with a standard method is able to enhance our understanding of emission mechanisms.

Correlation of the spectral hardness with the X-ray luminosity in bright X-ray pulsars

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In this work, I continue to develop a self-consistent numerical model of the polar radiation-dominated emitting region of a strongly magnetized accreting neutron star. The new simulations have been performed in the range of the mass accretion rates 10^{17}–5×10^{17} g/s onto one magnetic pole. They show that the induced scattering is a process playing a crucial role in the formation of the spectrum of the accretion column. At the accretion rates $\sim 10^{17}$ g/s the spectrum looks like a Bose-Einstein distribution corresponding to the temperature $T_\mathrm{r} \sim 7$ keV and the chemical potential that is much less than kT_r. Even under conditions of the Fermi energization of photons, the effect of the induced scattering provides the saturated emergent spectrum at higher accretion rates (at least, in the range studied). As the accretion rate increases to 5×10^{17} g/s, the temperature T_r reaches approximately 9 keV and the hardness ratio $F_{5-12\ \mathrm{keV}}/F_{1-3\ \mathrm{keV}}$ decreases slightly, being thus in the weak negative correlation with the X-ray luminosity.

A helium-burning white dwarf binary as a supersoft X-ray source

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Based on ROSAT, XMM and SRG/eROSITA data, we discuss the luminous supersoft X-ray source HP99 159 in the Large Magellanic Cloud (Greiner et al. 2023, Nature 615, 605). Optical spectroscopy reveals an accretion disk which is completely dominated by helium, suggesting that the donor star is hydrogen-free. We identify the accreting object as a white dwarf (i.e. another hydrogen-free star), which undergoes helium shell burning near its surface. While such systems have been predicted for more than 30 years including their appearance as supersoft X-ray sources, they have so far escaped detection. The properties of our system provide evidence for extended pathways towards Chandrasekhar-mass explosions based on helium accretion, in particular for stable burning in white dwarfs at lower accretion rates than expected so far. This may allow us to recover the population of the sub-energetic so-called Type Iax supernovae, up to 1/3 of all Type Ia supernovae, within this scenario.

Constraining the X-ray emitting regions in two eclipsing CVs with NuSTAR and XMM observations

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Eclipsing Cataclysmic Variables (CVs) provide an unique opportunity to investigate deeply into their X-ray emitting regions by disentangling the soft X-ray emission and the hard X-ray emission. For nova-like systems, the primary site of X-ray emission is considered to be located in between the standard, Keplerian part of the accretion disk and the slowly rotating white dwarf, whereas for an magnetized CV like an Intermediate Polar (IP), the primary site is the accretion column below a standing shock. Past observations of some CVs have revealed the presence of at least one secondary X-ray emission site whose nature is poorly understood. We present results from NuSTAR and XMM observations of two eclipsing CVs: UU Aqr, a nova-like variable, and V902 Mon, a highly obscured IP. The results from the timing studies and broadband X-ray spectrum is used to infer the sites of the X-ray emission.

Connecting recurrent novae with the lowest mass accretion rate neutron stars.

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Recurrent novae (RNe) are accreting white dwarfs with short recurrence times (less than about a century), so that at least two thermonuclear explosions or eruptions have already been observed. Only 11 galactic RNe are known to date. Extragalactic RNe with small recurrence times (< 10 years) are present in M31 and LMC. Because of their characteristics, RNe have similar local mass accretion rates ($\dot{m} = 1 - 100 g/s/cm^2$) to those of the lowest mass accretion rates on neutron star "bursters" ($\dot{m} =\ 50 g/s/cm^2$, recurrence time for thermonuclear bursts of the order 1 year). Here we compile and present recurrence times and mass accretion rates of RNe. We then compare, for the first time, these values with neutron star bursters, as well as thermonuclear ignition models (ranging over different mass accretion rates and fuel composition). We find that RNe extend the recurrence time vs. mass accretion rate relation of type I X-ray bursts, spanning 5 orders of magnitude in mass accretion rate and more than 8 orders of magnitude in recurrence time.

Observing X-ray lighthouses through a relativistic looking glass

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Pulse profiles of accreting X-ray pulsars are specific to the sources, usually clearly energy-dependent, often complex and variable in time. Their shapes and dependencies on energy, luminosity and time hold in principle a lot of diagnostic information on the emission geometry and emitted spectra but so far this has been rather little used. The underlying reason is the complexity of the overall problem and the struggle to obtain unique results in light of complex emission patterns, gravitational light-bending, geometrical effects and potential reprocessing in material close to the X-ray source. We present an overview of the observational data for classical accreting X-ray pulsars and of existing modelling efforts and results, indicating as well possibilities for progress in the future.

Highly Significant Detection of X-Ray Polarization from the Brightest Accreting Neutron Star Sco X-1

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The Imaging X-ray Polarimetry Explorer (IXPE) has successfully measured the X-ray polarization of Scorpius X-1, the brightest Z-source, in the 2-8 keV energy band. The degree of polarization was found to be 1.0% with a polarization angle of 8°. This measurement was conducted simultaneously with NICER, NuSTAR, and Insight-HXMT observations, enabling a detailed analysis of the source's broad-band spectrum across soft and hard X-rays. The source was observed for the majority of the time in its soft state, with occasional flaring. Furthermore, low-frequency quasiperiodic oscillations were observed. Through a spectro-polarimetric analysis, we determined that the accretion disk exhibits a polarization <3.2% (90% CL), the Comptonized component at higher energy a polarization of 1.3%, and an attempt to measure the polarization for the reflection component was also performed. Moreover, a rotation in X-ray polarization is observed compared to previous observations by OSO-8 and PolarLight, as well as with respect to the position angle of the radio jet. This finding suggests that the polarization may vary with the source's state, which means a change in the corona geometry with the accretion flow, or potentially indicating a relativistic precession.

The role of XMM-Newton in the investigation of persistent BeXRBs

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The persistent BeXRBs are a peculiar class of HMXRBs, which are characterized by persistent low X-ray luminosities ($L_X \sim 10^{34}$ erg s^{-1}) and wide ($P_{orb} > 30$ days), almost circular orbits. In these sources the NS is slowly rotating (with P_{spin} well above 100 s) and accretes matter directly from the wind of the companion Be star, without the formation of an accretion disk.

Since the '90s, when the first four members of this class were identified, several other sources of the same type have been discovered and investigated. Thanks to follow-up *XMM-Newton* observations, we have verified that most of them share common spectral and timing properties, such as a pulsed fraction that does not vary with the photon energy and a hot (kT = 1-2 keV) blackbody spectral component which contributes for 30-40 % to the total flux and has a size consistent with the estimated size of the NS polar cap.

Here we provide an overview of how *XMM-Newton* contributed to constrain the observational properties and the current understanding of this type of sources, and report about the first results obtained with a very recent *XMM-Newton* observation of the poorly known BeXRB 4U 0728-25.

Pulse-to-pulse Variations in the Accreting X-ray Pulsar Vela X-1

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Vela X-1 is an X-ray binary system formed by a neutron star and a supergiant. It is one of the best-studied X-ray binaries because it was detected early, shows persistent X-ray emission, and a rich phenomenology at many wavelengths. At time scales of individual pulses, important pulse-to-pulse variations have been observed. At low energies these variations can be related to absorption, while at high energies they can yield information about the X-ray emission geometry.

We have analysed three XMM-Newton observations of Vela X-1 from 2000, 2006 and 2019 and present the results of a systematic study of pulse-to-pulse variations. For this study we have analysed the differences between the extracted light curves and synthetic light curves, created by repeating the mean pulse profile and scaling it appropriately. In addition, we have studied variations of the pulse profile shape with time and flux over longer time scales.

The light curves occasionally show strong variations from one pulse cycle to the next, but also longer stretches of similar pulsations. In all observations we find time- and flux-dependent pulse shapes within the observation but also systematic differences between the three observations.

Discovery of spin-phase-dependent QPOs in the supercritical accretion regime from the X-ray pulsar RX J0440.9+4431

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RX J0440.9+4431 is an accreting X-ray pulsar (XRP) that remained relatively unexplored until recently, when major X-ray outburst activity enabled more in-depth studies. Here, we report on the discovery of $\sim$0.2 Hz quasi-periodic oscillations (QPOs) from this source observed with Fermi-GBM. The appearance of QPOs in RX J0440.9+4431 is triple transient, that is, QPOs appear only above a certain luminosity, only at certain pulse phases (namely corresponding to the peak of its sine-like pulse profile), and only for a few oscillations at time. We argue that this newly discovered phenomenon (that is, the appearance of triple transient QPOs – or ATTO) occurs if QPOs are fed through an accretion disk whose inner region viscosity is unstable when exposed to mass accretion rate and temperature variations. Such variations are triggered when the source switches to the supercritical accretion regime and the emission pattern changes. We also argue that the emission region configuration is likely responsible for the observed QPOs spin-phase dependence.

Probing the Atoll/Z Continuum with Neutron Star Low Mass X-ray Binary 1A 1744-361

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Neutron star low mass X-ray binaries (NS LMXBs) have traditionally been broken into two classes based on their spectral and timing properties, as well as their positions on the X-ray color-color diagram. We report on X-ray (NICER/NuSTAR/Swift/MAXI) timing and spectroscopic results and radio (MeerKAT) observations from a three-month monitoring campaign in 2022 of NS LMXB 1A 1744-361. The X-ray observations suggest that 1A 1744-361 spent the majority of the outburst in an atoll state, but we discovered that the source exhibited properties consistent with traditional Z-sources at the outburst peak. The source showed normal branch-like quasi-periodic oscillations (NBO-like QPOs, NBOs) with a fractional rms amplitude of 5%, which we connect to the NBOs seen in traditional Z-sources. MeerKAT monitoring data in the radio showed that the source was at its radio-brightest during the outburst peak, and the source transitioned from the 'island' to the 'banana' spectral state within 3 days of the outburst onset, launching transient jet ejecta. We thus show that atoll- and Z-sources are not two distinct source classes, but instead represent two states on a mass accretion rate continuum; thus, 1A 1744-361 probes the boundary between the atoll- and Z-states.

Probing the propeller regime with symbiotic X-ray binaries

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At the moment, there are two neutron star X-ray binaries with massive red supergiants as donors. De et al. (2023) proposed that the system SWIFT J0850.8-4219 contains a neutron star at the propeller stage. We study this possibility by applying various models of propeller spin-down. We demonstrate that the duration of the propeller stage is very sensitive to the regime of rotational losses. Only in the case of a relatively slow propeller model proposed by Davies and Pringle (1981), the duration of the propeller is long enough to provide a significant probability to observe the system at this stage. Future determination of the system parameters (orbital and spin periods, magnetic field of the compact object) will allow to put strong constraints on the propeller behavior.

XMM-Newton observations of the peculiar Be X-ray binary A0538-66

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A0538-66 is a neutron star/Be X-ray binary located in the LMC and, since its discovery in the seventies, it showed a peculiar behavior which makes it an unique object in the high-mass X-ray binaries scene: the extremely eccentric orbit (e=0.72), the short spin period of the neutron star (P=69 ms), the episodes of super-Eddington accretion. These characteristics contribute to a remarkable bursting activity that lasts from minutes to hours and increases the flux of a factor $10^3 - 10^4$.

In 2018, A0538-66 was observed by XMM-Newton in a particularly active state, characterized by a forest of short bursts lasting 0.7-50 seconds each.

In this contribution we present the analysis of these observations. The timing analysis allowed us to distinguish between the epochs of direct accretion and propeller state, that do not correlate with the orbit position of the neutron star. The spectral analysis revealed that during the accretion regime three components (a soft thermal, a hard non-thermal, a 6.4-keV emission line) equally contribute to the overall emission, while the propeller regime is characterized by a single soft component.

We discuss these findings in the context of spherical and disk accretion regimes, highlighting the similarities and the differences with other X-ray binary systems.

Accreting White Dwarfs in the X-ray + Optical Sky with SRG/eROSITA and ZTF

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The X-ray sky is being transformed through data releases from the SRG/eROSITA mission, which is the deepest all-sky X-ray survey in nearly thirty years. Furthermore, Gaia information enables the distinction between Galactic and extragalactic sources, which was difficult in the past. If that's not enough, the Zwicky Transient Facility (ZTF) has been collected optical photometry down to 21 mag across the entire Northern sky for five years. I will present a survey of accreting white dwarfs, from cataclysmic variables to symbiotic stars, that has emerged from a crossmatch of SRG/eROSITA + Gaia + ZTF. New relationships in orbital periods, X-ray luminosity, white dwarf spin periods, and variability are emerging, which will inform our current understanding of binary star evolution in ways not seen before. I will also focus on the ultracompact binary population of white dwarfs in the X-ray, and the implications for mergers and populations seen in gravitational waves with LISA.

Blind Source Separation for Decomposing X-ray Pulsar Profiles

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Accretion-powered X-ray pulsars provide a unique opportunity to study physics under extreme conditions. To fully exploit this potential, however, the interrelated problems of modelling the radiative transport and the dynamical structure of the accretion flow must be solved. This task is challenging from both a theoretical and an observational point of view, and is further complicated by the lack of direct correspondence between the properties of the emission coming from the neutron star and those observed at a distance. In general, a mixture of emission from both poles of the neutron star, viewed from different angles, is indeed observed at some or even all phases of the pulse cycle. It is therefore essential to reconstruct the contributions of each pole to the observed flux in order to test and refine models describing the formation of X-ray pulsar spectra and pulse profiles. In this talk, I present a novel data-driven approach to address this problem using the pulse-to-pulse variability in the observed flux, and demonstrate its application to RXTE observations of the bright persistent X-ray pulsar Cen X-3. I then discuss the comparison of our results with previous work that attempts to solve the same problem.

Self-similar accretion modes between accreting white dwarfs and neutron stars

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In this talk I will focus on the variability properties of accreting white dwarfs, and show how the Kepler and TESS missions have allowed us to characterise broad-band aperiodic and quasi-periodic variability in unprecedented detail. I will show how the striking phenomenological similarities between accreting white dwarfs and accreting neutron stars can allow us to test models of the underlying physics of disk accretion. Specifically I will introduce various accretion modes observed in accreting white dwarfs that have a direct analogy to X-ray binaries with neutron star accretors, including mode transitions, Type-I thermonuclear bursts and Type-II magnetically driven X-ray burst.

Insights from Swift J0243.6+6124 during its 2017-2018 outburst

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Swift J0243.6+6124 is a Be/X-ray binary system and the first galactic ultra-luminous X-ray pulsar, discovered in 2017, with its luminosity reaching up to $\sim 10^{39}$ erg/s. We conducted timing and noise analysis of the source during its 2017–2018 outburst. New spin frequency measurements are obtained by pulse timing analysis on the *NICER*/XTI data, enhancing the *Fermi*/GBM frequency history. A transition from double-peaked to single-peaked pulse profiles is uncovered at $\sim 7 \times 10^{36}$ erg/s. This previously unreported transition is suggested to be consistent with a change from a hybrid beam to a pencil beam emission near the magnetic poles, implying a dipolar magnetic field strength of $\sim 5 \times 10^{12}$ G. We also examined timing noise by generating a power density spectra of the spin frequency derivative fluctuations. At the super-Eddington luminosities, the noise strength estimates are highly elevated. We suggest that this may indicate the dominance of the quadrupole fields as the pulsar magnetosphere is getting more compact at such high accretion and luminosity levels.

Magnetic fields of neutron stars in Be X-ray binaries: what can we learn from modelling and observations in quiescence?

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For accreting neutron stars in high-mass X-ray binaries, accessing the strength and configuration of their magnetic fields stands as a fundamental problem, critical for advancing our understanding of magnetic accretion. Be X-ray binaries are the most promising candidates for obtaining this information since they allow us to probe accretion onto the neutron star with a magnetic field of the same strength and configuration over a large range of mass-accretion rates. Recent observations revealed that the intermediate and hard X-ray continuum at dim, quiescent states, can provide principally new information about the surface magnetic field. This method of the magnetic field diagnostic is alternative to cyclotron line measurements. Most importantly, the quiescent state is associated with a simplified physical picture of accretion, wherein the flow decelerates within the neutron star atmosphere, in contrast to the extended accretion column at higher rates of mass supply. We present detailed modelling of spectral formation combined with relativistic ray tracing to describe low-luminosity accretion onto a strongly magnetised neutron star. This model, when applied to observations of Be X-ray binaries in quiescence, allows for the estimation of their magnetic fields and the determination of the location of the accreting poles on the neutron star surface.

Disk torque models in comparison

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Accreting x-ray bright objects show a variety of patterns in their spin period evolution. With the availability of decades of observations of accreting neutron stars, where precise spin measurements are possible due to strongly beamed emission resulting in clear detection of pulsations, the connection between mass accretion and spin evolution can be explored. Several modes of accretion are proposed to explain the observed behavior.

A number of models have been suggested to describe the accretion of matter onto a magnetized and rotating object from a disk. Their successful application to spin measurements allows to infer important parameter values of the system, most crucially the magnetic field strength. However, differences in their formulation hinder direct comparison of the obtained results and render the interpretation challenging. Here, I present a generalized reformulation of a number of accretion torque models, that enables a straightforward comparison.

This approach, combined with the findings from magneto-hydrodynamic simulations and decades of observational data, allows us to understand principal differences in systems, and to turn spin evolution measurements into a reliable method for assessing magnetic field strengths.

10 years of SALT optical spectroscopic monitoring of Be X-ray binaries

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High-mass X-ray binaries (HMXB) are one of the most numerous class of interacting binary. They offer the chance to observe extreme physics in high magnetic field and strong gravitational environments. A large fraction of HMXBs comprise a neutron star and a Be star, which is characterised by an equatorial 'decretion' disc from which the neutron star periodically accretes. Studying the interaction between the Be star, disc and compact object is central to our understanding of the formation and evolution of these systems. Whilst X-ray all-sky monitors have built up excellent long-term light curves of the accretion events in HMXBs, our optical coverage, particularly spectroscopic, has been much sparser. We present here details of our 10 year Southern African Large Telescope (SALT) optical spectroscopic monitoring programme of the Be counterparts of Galactic and Magellanic HMXBs. The long baseline of these observations, along with good cadence, resolution & S/N make this one of the best available optical spectroscopic datasets in the field, and a valuable resource for observers and theoreticians alike. We discuss some of the science that our team is doing with this data, and our plans to release the full catalogue to the community.

Evolution of a 30-yr-duration post-nova pulsating supersoft source in the Large Magellanic Cloud

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Supersoft X-ray sources (SSS) may host White Dwarfs accreting from binary companions and undergoing nuclear burning of the accreted material on their surface. Here we report on the X-ray and optical properties of 1RXS J050526.3-684628, a SSS located in the Large Magellanic Cloud (LMC). The long term evolution is characterized by a slow rise and a sharp decay over 3 decades (based on ROSAT, XMM-Newton, eROSITA, Swift observations). XMM-Newton observations (2014 & 2017) allowed us to constrain its nature and identify pulsations with a period of ~170 s, while a recent XMM-Newton visit (i.e. Jan. 2024) enabled us to study the evolution of its spectral and temporal properties. Interestingly the pulse profile shape has changed significantly and the WD span-up for about 0.1 sec within 7 years. All the above point to an evolving post novae SSS. By comparison with existing models, we find that the effective temperature and luminosity evolution are consistent with an $\sim 0.7\ M_{\odot}$ carbon-oxygen white dwarf accreting at a rate of $\sim 10^{-9}$ $M_{\odot} yr^{-1}$. Our results suggest that there may be many more undiscovered SSSs and 'missed' novae awaiting dedicated deep X-ray searches in the LMC and elsewhere.

Unveiling the Role of Magnetic Field in Generating Quasi-Periodic Oscillations: Insights from Accreting White Dwarf Systems

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Almost all accreting X-ray binary systems (XRBs) exhibit prominent brightness variations on a few characteristic time-scales and their harmonics. These quasi-periodic oscillations (QPOs) are thought to be associated with the precession of a warped accretion disc, but the physical mechanism that generates the precessing warp remains uncertain. Relativistic frame dragging (Lense-Thirring precession) is one promising candidate, but a misaligned magnetic field is an alternative, especially for neutron star XRBs.

Here, we report the discovery of 5 accreting white dwarf systems (AWDs) that display strong optical QPOs with characteristic frequencies and harmonic structures that suggest they are the counterpart of the QPOs seen in XRBs. Since AWDs are firmly in the classical (non-relativistic) regime, Lense-Thirring precession cannot account for these QPOs. By contrast, a weak magnetic field associated with the WD can drive disc warping and precession in these systems, similar to what has been proposed for neutron star XRBs.

Our observations confirm that magnetically driven warping is a viable mechanism for generating QPOs in disc-accreting astrophysical systems, certainly in AWDs and possibly also in (neutron star) XRBs. Additionally, they establish a new way to estimate magnetic field strengths, even in relatively weak-field systems where other methods are not available.

NICER observations of Nearby Persistent Supersoft X-Ray Sources

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Supersoft X-ray sources (SSSs), known for their distinct spectral properties emitting predominantly at lower energies (i.e., below 1 keV), have remained a focal point in astrophysical studies due to their association with various evolutionary stages of white dwarf binaries and potential insights into white dwarf accretion processes. In this study, we utilize data collected by the Neutron Star Interior Composition Explorer (NICER) to study five persistent SSSs 1E-0035.4-7230, 1E-0056.8-7154, CAL83, RXJ0019.8+2156, and RXJ0925.7-4758 in close proximity. In the X-ray spectral analyses, most of the blackbody temperatures of the SSSs were stable among the observations, but some of them showed significant temperature changes, indicating that the accretion process can vary on weekly/monthly timescales. We also find that some SSSs exhibited strong variability in the X-ray light curves. More interestingly, we detected a potential periodic signal indicative of the spin period of a white dwarf, observed in multiple NICER datasets.These results from the campaign have the potential to significantly advance our knowledge of SSSs and their X-ray spectral/timing properties, making important contributions to the field.

Chapter 7

Thermonuclear explosions: X-ray bursts and novae

Burst-Disk Interaction in 4U 1636-536 as Observed by NICER

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In this talk we summarize our findings based on NICER, ASTROSAT and NuSTAR observations of the thermonuclear X-ray bursts observed from the prolific low mass X-ray binary 4U 1636-536. We first report the detection of 51 new X-ray bursts detected by NICER in between 2017 and 2022. We performed time resolved X-ray spectral analysis on 40 of these bursts and found that at least three show evidence of photospheric radius expansion. Overall we found that the classical fixed background subtraction method does not provide adequate fits to the observed burst spectra and in 63% of the spectra a scaling factor to the persistent emission is statistically needed. The scaling factor is attributed to the increased mass accretion rate onto the neutron star due to Poynting-Robertson drag. We will also present our results for time-resolved spectral analysis of five X-ray bursts simultaneously observed by NICER and AstroSat, confirming our results with even greater precision thanks to the broad energy range covered with NICER and LAXPC. Finally, we show that the bursts observed with NuSTAR show significant evidence for Compton cooling.

A catalogue of long thermonuclear X-ray bursts

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Rare ($< 1\%$), but energetic thermonuclear (Type I) X-ray bursts that take place in the surface layers of accreting neutron stars are, based on their temporal extent, classified either as superbursts or intermediate-duration bursts. The latter ones last a few to tens of minutes and are thought to correspond to the long cooling of a thick ($\sim 10m$) helium layer, while the hour-long superbursts are attributed to the detonation of an underlying carbon layer. Here we present the catalogue compiled by Alizai et al. (MNRAS 521, 3608, 2023) that contains a total of 84 long bursts from 40 low-mass X-ray binary sources, found with 14 space missions since 1969. These long bursts fulfill three physical selection criteria (energy release, duration of the photospheric radius expansion, and burst timescale) distinguishing them from the shorter, frequently observed thermonuclear bursts. The catalogue includes burst peak fluxes and fluences, as well as source accretion rates at burst onset, which allows us to find statistical trends for these long bursts. We discuss whether long bursts represent a separate population of thermonuclear bursts or rather are part of one same continuum.
A database of the obtained light curves and spectroscopic results is also available.

A series of NICER Thermonuclear Bursts from UCXB M15 X-2

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This poster presents the preliminary results of a study on Type I X-ray bursts observed in the ultracompact X-ray binary 4U 2129+12, found in the globular cluster M15. UCXBs and their hydrogen-poor companions make for interesting case studies of the accretion environment and the neutron star atmosphere in bursters. After detecting an X-ray burst in September 2022, the Neutron Star Interior Composition Explorer (NICER) has extensively monitored the 2022 outburst of this source. We have analyzed the data from these follow-up observations and have identified a total of 5 additional X-ray bursts. We have performed time-resolved spectroscopy and found evidence of deviations from a blackbody in the spectra of all the bursts. We significantly improved the fit by taking into account the enhanced persistent emission and have compared the results to those obtained through neutron star atmosphere models. We have also studied the fuel composition, which points to helium bursts. Further analysis of these results is currently being conducted.

Burst oscillations from 4U 1728-34 observed with NICER

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We present our results on the detected burst oscillations before or during the observed thermonuclear X-ray bursts from low mass X-ray binary 4U 1728-34 with NICER. We observed 11 X-ray bursts from the system with NICER and in 6 of these events, we detected burst oscillations, at the previously observed frequency of about 363 Hz. Most interestingly, we also observed oscillations just prior to the onset of 2 bursts. We show that the oscillations started to become significant 2s before and ceased at the onset of the bursts. We discuss the implications of these unexpected findings with respect to possible flame propagation scenarios.

Mass-loss and composition of wind ejecta in type I X-ray bursts

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X-Ray bursts (XRB) are powerful thermonuclear events on the surface of accreting neutron stars (NS), which can synthesize intermediate-mass of the material may be ejected by radiation-driven winds.

A modern non-relativistic radiative wind model was linked through a new technique to a series of XRB hydrodynamic simulations, that include over 300 isotopes. This allows us to construct a quasi-stationary evolution of the XRB+wind.

We determine the mass-loss and chemical composition of this wind ejecta and its significance for Galactic abundances. We also report on the evolution of observational quantities during the wind phase, which can help constrain the mass-radius relation in NS.

Results show 0.1% of the envelope mass ejected per burst, at an average rate of 2.6% the accretion rate, and 90% of the ejecta composed by ^{60}Ni, ^{64}Zn, ^{68}Ge and ^{58}Ni. The ejecta also contained traces of some light p-nuclei, but not enough to account for their Galactic abundances.

The photospheric magnitudes showed remarkable correlations that could be used to link observable quantities to the physics of the envelope's interface with the NS crust. This is a promising result regarding the issue of NS radii determination.

Type-I X-ray Bursts in the X-ray Eclipses of EXO 0748-676

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Neutron star (NS) X-ray binaries (XRBs) that irradiate and ablate their companion star are called false widows and represent an intermediate state between X-ray binaries and spider pulsars. The presence of ablated material gives rise to several characteristics, including asymmetric, energy-dependent and highly variable eclipses in sufficiently inclined systems. EXO 0748-676, formally a NS low-mass XRB, was recently classified as a false widow based on its extended and asymmetric eclipses created by an X-ray irradiation-driven ablated outflow and evidence of 551 Hz X-ray and Radio pulsations. EXO 0748-676 was observed regularly by the Rossi X-ray Timing Explorer (RXTE) and XMM-Newton during its 24-year-long outburst, which captured hundreds of eclipses and many Type-I thermonuclear X-ray bursts. Here, I discuss the potential origins of 20 Type-I X-ray bursts observed by RXTE that appear during eclipse phases, 10 of which occur entirely during totality, and all occur while the source is in the hard spectral state. These in-eclipse X-ray bursts likely arise from reflection off of an ionised medium, possibly the ablated outflow, as the reflected flux from the outer accretion disc is insufficient to cause the burst emission to be visible during eclipses.

Fast winds blowing from a white dwarf left by the historical supernova 1181 and its X-ray emission

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A historical supernova 1181 is a type Iax supernova that is thought to be caused by a binary white dwarf merger. Interestingly, inside of this supernova remnant, a massive white dwarf was found. Optical observations reveal that, from this white dwarf, the very fast wind of about 15,000 km/s is blowing, forming wind termination shock inside the supernova remnant by colliding with the supernova ejecta. The gases shocked by both the termination shock and the outer supernova remnant shock are expected to be sources of luminous X-ray emission. In this talk, we report the results of our analysis of X-ray observations of this source using XMM-Newton and Chandra. In addition, based on these observations, we have developed a theoretical model that explains the two-layer shock structure of the supernova remnant and the wind termination shock, and we find the fast wind from the white dwarf started blowing only in the recent tens of years, even though the supernova happened almost 1000 years ago. We will also explain our theoretical model and its implications for future observations.

The crucial discovery of thermonuclear X-ray bursts: never throw away old data!

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Close to 50 years ago, the Astronomical Netherlands Satellite (ANS) was launched on 30 augustus 1974. Onboard were 2 X-ray experiments, SXX (0.2-7 keV) and HXX (1-30 keV), and 1 UV-spectrophotometer. One of the main achievements of ANS is the discovery of Type I, thermonuclear, X-ray bursts from 4U 1820-30 in the globular cluster NGC 6624. The SXX data have been retrieved from microfiche. We revisit this crucial discovery (Type I X-ray bursts are markers of neutron stars), and compare the burst properties to those derived from modern observations. Lesson learned: never throw away old data!

The meaning of quasi-simultaneous X-rays and gamma-rays observations of RS Oph in outburst

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In 2021 the symbiotic recurrent nova RS Ophiuchi had a luminous nova outburst, followed with instrumentation ranging from Cherenkov to radio telescopes. There was significant, measurable gamma-ray emission for the first 3 weeks both in the GeV range and in the range of hundreds of GeV. While the X-ray monitoring was limited to the X-ray band below 12 keV, on day 9 of the outburst a NuSTAR exposure in the 3-79 keV range was done over a little more than 24 hours. The hard X-ray observations is precious to track the origin of the shocks and it seems that at least the particle acceleration causing the gamma-rays detected with Fermi occurred in the shocked plasma detected with NuSTAR. Only upper limits were measurable for a possible non-thermal power-law component, indicating that the gamma-ray origin was most likely hadronic. As the shocked material cooled, high resolution X-ray spectra were obtained with Chandra and XMM, giving further indications on the origin of the shocks. We will discuss how the shocks nay have originated and in which "sites" in this complex symbiotic system.

Thermonuclear explosions on neutron stars reveal the speed of their jets

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Relativistic jets are observed from accreting and cataclysmic transients throughout the Universe. Despite their importance, their launch mechanism is not known. For accreting neutron stars, the speed of their compact jets can reveal whether the jets are powered by magnetic fields anchored in the accretion flow or in the star itself, but to-date no such measurements exist. Using Type-I X-ray bursts from the neutron star, we have developed a new method to measure this compact jet speed: if the jet responds to the X-ray bursts, the frequency-dependent time delays in the radio band constrain the jet properties. Combining simultaneous INTEGRAL and ATCA observations, we detect bright flares in the jet emission for a few minutes after each X-ray burst in 4U 1728-34 and 4U 1636-536. We interpret these flares as a response to enhanced mass accretion rate triggered by the X-ray bursts. With these flares, we measure the speed of the compact jet to be v=0.38c, much slower than those from black holes at similar luminosities, and consistent with the expected neutron star escape velocity. This discovery provides a new tool to determine the role of individual system properties on jet speed, revealing the dominant jet launching mechanism.

Old novae in the eROSITA survey

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Nova explosions are thermonuclear events on top of an accreting white dwarf in a cataclysmic variable (CV) or a symbiotic system. The nova event results in the increase of the optical luminosity by 7-8 orders of magnitude. That makes the nova outburst detectable at any distance in the Galaxy, in the Local Group, and even beyond the Local Group. However, due to the resulting distance distribution of novae, the host system remains unknown for most cases. Accretion powers X-rays in the host system once the mass transfer is resumed and the white dwarf starts to accrete again. We search for old nova host systems in the German data of the eROSITA survey. A total of 31 old novae are identified, with about 2/3 of the identifications being new detections in the X-rays of the old nova systems. Several of them are IP candidates, so increasing the fraction of known novae outbursts occurring in magnetic systems.

Modelling the post-outburst thermal X-ray emission from classical novae

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We present new 1-D models of classical novae using the stellar evolution code MESA. For the first time we combine convective overshoot during the thermonuclear runaway with element diffusion during the full evolution of the multi-cycle nova models. We include interaction with the companion into the mass loss scheme. The models predict duration, luminosity and effective temperature of post-nova optical and soft X-ray emission. This will allow comparisons to observations of nova and post-nova sources, constraining system parameters such as the white dwarf mass. We test the model against available data for selected novae and present the result of these comparisons.

Chapter 8

Ultra luminous X-ray sources

Investigating the ULX population with machine learning techniques

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Ultraluminous X-ray sources (ULXs) are extragalactic X-ray binaries with luminosities exceeding the Eddington limit for a 10 Solar masses black hole (BH). Out of thousands of ULXs found so far, only a few show pulsations, a clear indication of the compact object being a neutron star (NS) likely accreting at super-Eddington regimes. Ideally, searching for pulsations is the best way to find and identify new NS-ULXs. In reality, this has proven to be a rather difficult task. Pulsations are often transient and search techniques require high-statistics observational data, difficult to acquire with the state-of-the-art X-ray satellites. As a consequence, the nature of the compact object for the majority of ULXs remains unknown, pointing out the need to find alternative methods to discern between BH- and NS-ULXs. To this aim, we applied unsupervised machine learning (clustering) algorithms to 4XMM-DR13 data of ULXs. Preliminary results show that pulsating and non-pulsating ULXs are assigned to different clusters, on the basis of observational parameters that are usually overlooked in more traditional types of analysis. This approach holds great potential in identifying promising NS-ULXs candidates as targets for future observational campaigns and in obtaining data-driven estimates of the ULX demography.

X-ray spectral variability as a probe of the compact objects powering ULXs

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The nature of the accretor in most ultraluminous X-ray sources (ULXs) has remained unknown with the exception of a few ULXs unambiguously identified as pulsating neutron star accreting at super-Eddington rates. In this talk, I will present a novel method to estimate the nature of the accreting compact objects by accurately tracking the Luminosity-Temperature (L-T) diagram. We used data collected with the XMM-Newton satellite for several ULXs and modelled the spectra with a double thermal component. In some ULXs such as those in the NGC 5204 and NGC 1313 galaxies, there are significant deviations from the expectation of thin disc models. This occurs particularly at high luminosities. Such deviations are likely due to the accretion rate exceeding the supercritical rate with a consequent launching of powerful winds and deformation of the accretion disc. This interpretation allows us to forecast the mass of the compact object and, therefore, its nature which in some cases, e.g. Holmberg II X-1, is likely a black hole and in others, e.g. NGC 1313 X-2, is a neutron star.

The Orbit of NGC 5907 ULX1

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I will report on the orbit of the binary system powering the most extreme ultraluminous X-ray pulsar known to date: NGC 5907 ULX1. This source has been the target of a substantial multi-instrument campaign, mainly in the X-ray band, but no clear counterparts are known in other bands. Although it is highly variable and pulsations can be transient, regardless of the source flux, the timing data collected so far allow us to investigate the orbit of this system. We find an orbital period of $5.7^{+0.1}_{-0.6}$ d and a projected semi-axis for the pulsar of $3.1^{+0.8}_{-0.9}$ lts. By enforcing orbital-phase coherence we obtain a precise and full orbital ephemeris. However, there are 6 similar solutions, less likely but still acceptable within 3 sigma. I will discuss the implications of these findings for the nature and geometry of this system and in the context of other X-ray binaries and in particular ultraluminous X-ray pulsars.

Modeling the emission and polarization properties of Pulsating Ultraluminous X-ray sources

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Pulsating Ultraluminous X-ray Sources (PULXs) are a class of extragalactic sources with high X-ray luminosity, in excess of 10^{39} erg s^{-1}, and showing pulsations that associate them with neutron stars accreting at a super-Eddington rate. A simplified model is presented, which describes the thermal emission from an accreting, highly magnetized neutron star and includes the contributions from an accretion disk and an accretion envelope surrounding the star magnetosphere. Through numerical calculations we determine the flux, pulsed fractions, polarization degree, and polarization angle considering various viewing geometries. The model is confronted with the *XMM-Newton* spectra of two PULXs, M51 ULX-7 and NGC 7793 P13, and the best fitting viewing geometries are estimated. A measurement of the polarization observables, which will be available with future facilities, along with spectroscopic data obtained with *XMM-Newton*, will provide considerable additional information on these sources.

The long-term variability of a population of ULXs monitored by Chandra

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We report on the results of a Chandra Large Program to monitor the ULX populations of three nearby ULX-rich spiral galaxies over the course of a year. The ULX population shows a variety of long-term variability behaviour. A small number of ULXs show completely persistent flux, though the majority of ULXs show moderate levels of variability with a significant relationship between hardness and luminosity consistent with a supercritically accreting source with varying accretion rate. Some ULXs show very high-amplitude variability that does not appear to be bimodal like that expected for sources undergoing the propeller effect, but may instead indicate the presence of high-amplitude superorbital periods, a feature also demonstrated by most neutron star ULXs, and may indicate that these sources are good candidates for future pulsation searches.

The surprising long-term evolution of the ULXP NGC 7793 P13

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Persistent Ultra-luminous X-ray Pulsars (ULXPs) allow us to monitor and study the behaviour of some of the brightest neutron stars in the universe over extended periods of time. Here I will present our multi-wavelength study of the archetypical ULXP NGC 7793 P13 over the last 8 years. After showing a very stable spin-up between 2017–2020, which was independent of the observed X-ray flux, the source has started to spin-up stronger since last year, while at the same time reaching historic highs in X-rays, and historic lows in UV flux. I will discuss these latest measurements in the context of the long-term variation and evolution of the system and their context to the broad-band spectrum. I will present different physical scenarios to explain this behaviour, which might be driven by a large precessing accretion disk interacting with a very strong magnetic field. Our results show how important continued monitoring of these sources is to increase our understanding of super-Eddington accretion and the magnetic field configuration of neutron stars.

The QPOs awaken in the quest for pulsating ULXs

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The discovery of pulsating ultraluminous X-ray sources (PULXs) has shown that accreting neutron stars' luminosities can exceed 500 times their Eddington limit, offering for the first time a way to test our theories about the super-Eddington accretion regime. M82 X-2, the prototypical PULX, has also shown (at least once) quasi-periodic oscillations (QPOs) in the mHz range. This type of variability observed in ULXs has been previously interpreted as the footprint of an accreting intermediate-mass black hole, but the presence of mHz-QPOs in a ULX powered by an accreting neutron star demonstrates that this feature is ubiquitous to black holes and neutron stars alike. Thanks to a dedicated project we recently discovered mHz-QPOs in the power spectra of other two PULXs, M51 ULX-7 and NGC 7793 P13, suggesting that this feature may be a common property of this class of sources. More importantly, the presence of mHz-QPOs seems to correlate with a significant decrease in the spin pulsed fraction, potentially compromising the detection of coherent signals in PULXs. Nonetheless, if the two features are intertwined, the study and comparison of the QPOs properties could represent an additional tool to identify new PULXs.

Decomposing the X-ray spectrum of ultra-luminous X-ray pulsar NGC 7793 P-13

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We performed a spectral decomposition of NGC 7793 P-13 on an XMM-Newton data set taken on 2019/11/28 by employing a method developed through studies on active galactic nuclei. The method decomposed the X-ray continuum into two components: one that varies with the X-ray pulsation and the other that does not. The latter component exhibits a spectrum extending up to ~ 7 keV that is explicable as a combined emission of a 0.4 ± 0.2 keV standard disk with an inner radius of 150^{+140}_{-90} km and a $1.1^{+1}_{-0.3}$ keV blackbody emission with a ~ 30 km radius. The obtained inner disk radius and luminosity are consistent with a scenario that the neutron star magnetic field truncates the accretion disk at the magnetospheric radius. The blackbody component likely originates in either a super-critical flow formed around the magnetospheric radius or emission reprocessed at the inner edge of the accretion disk. As for the variable component, it exhibits a continuum with a photon index of $0.2^{+0.4}_{-0.6}$ and an emission line at ~ 1 keV. The origin of the line can be either emission scattered at the inner edge of the accretion flow formed outside the magnetospheric radius or that of plasma trapped inside the neutron star's magnetic field.

Exploring the nature of ultra-luminous X-ray sources across stellar population ages using detailed binary evolution calculations

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Theory suggests that neutron stars (NSs), not black holes, dominate the intrinsic ultra-luminous X-ray source (ULX) populations, even though the majority of the observed sample is non-pulsating (pulses hint at accreting NSs). Using POSYDON, we simulate large populations of X-ray binaries, covering a range of starburst ages from 5 to 1000 Myr. Following predictions for the alignment of the NS spin and accretion disc, we estimated the required mass accreted by NSs in ULXs so that observable X-ray pulses are suppressed. While we find that the properties of ULXs are sensitive to model assumptions, there are certain trends that populations follow. Young and old stellar populations are dominated by BHs and NSs, respectively. The donors are massive hydrogen-rich main-sequence stars in young populations (< 100 Myr) and low-mass hydrogen-rich giant stars in older populations (> 100 Myr), with helium-rich stars dominating around 100 Myr. We find NS ULXs exhibiting stronger geometrical beaming than BH ULXs, leading to an underrepresentation of NS accretors in observations. Coupled with our finding that X-ray pulses are suppressed in at least 60% of the NS ULXs, we suggest that the observed fraction of ULXs with detectable X-ray pulses is very small, in agreement with observations.

Harnessing the power of groups for pulsating ULX demography

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Unsupervised clustering algorithms are an example of unsupervised artificial intelligence and allow the automatic grouping of data in diverse fields. Their ability to discover patterns in data is valuable in many contexts, as they are independent from prior knowledge. A promising field for the applicability of unsupervised algorithms is the search for candidate pulsating ultraluminous X-ray sources (PULXs), on the basis of their observational properties. The discovery of pulsations in ULXs is challenging and time-consuming, and as a result, only a few PULXs have been discovered so far. The employment of clustering techniques would significantly speed up the advances in the field. This research focuses on identifying the observational parameters and the intrinsic characteristics that make PULXs stand out against the general population of known ULXs. Several clustering algorithms are compared on 4XMM-DR13 data of ULXs. They all show that PULXs have distinctive properties and identify promising PULX candidates with similar characteristics. Explainability techniques widely used in artificial intelligence are applied to provide the astrophysics community with easily interpretable results. This approach not only overcomes the limitations of traditional pulsation-based identification but also offers a practical tool for targeted observations and demographic estimations.

Spectral studies of super-Eddington accreting Neutron Stars in the Magellanic Clouds

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Major outbursts of BeXRBs offer a unique laboratory for study of accretion onto magnetized neutron stars (NS) over a large dynamic range. The accreting material is entrained from the accretion disk by the strong magnetic field, and then channeled onto the NS, forming a so-called accretion column (AC). Physical simulation of the AC requires consideration of a variety of physical processes occurring in strongly magnetized plasma, including complex multi-dimensional radiative transfer and the presence of radiation-dominated shocks. Some models (e.g. Becker+Wolff 2007), have proven successful at reproducing the observed AC spectra in super-critical sources, in which radiation pressure plays a dominant role in controlling the dynamics of the accreting material. Alternatively, a self-consistent model for the AC (West+ 2017) is based on an iterative method that yields simultaneous, coupled solutions for the radiation-hydrodynamical structure of the accretion column, along with the radiation distributions escaping from the AC. In this study we will focus applications of the above models in spectra obtained during super-Eddington outbursts of BeXRBs in the Magellanic Clouds. In our case-study of RXJ0209.6-7427, we track changes in the AC structure and the emission patterns at the limit of 10^{39} erg/s.

Chapter 9

Population studies

Shedding light on quiescent X-ray Binaries through population studies with eROSITA.

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X-ray binaries (XRBs) are our most accessible way to probe populations of Galactic compact objects in the X-ray regime, and offer crucial constraints on Galactic stellar evolution models. XRB studies began with the brightest sources discovered during outbursts, followed by detections of relatively fainter sources by survey missions. Previously reported distributions of XRBs plateau at intermediate luminosities of 10^{35} erg/s, and only reach fluxes down to a few 10^{-12} cgs. eROSITA's improved sensitivity allows us to extend this further by a factor ≥ 10, reaching the little explored low luminosity regime, providing improved constraints on the log(N)-log(S) distributions of both persistently faint XRBs and transients in quiescence.

We present log(N)-log(S) distributions of high mass (HMXBs) and low mass X-ray binaries (LMXBs), as obtained using eROSITA detections of nearly 150 XRBs in the western Galactic hemisphere, with comparisons to previous missions, reproduced after additionally taking variability effects into account. Since eROSITA detections are a proxy for persistent or quiescent activity, we report on neutron star HMXBs that remain observable at low luminosities even when not in outburst (long considered off states). Further, we remark on eROSITA's discovery of several such neutron star HMXBs, providing new test cases for low luminosity accretion.

Searching the non-accreting white dwarf population in eROSITA data

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The first all-sky X-ray survey was performed by the ROSAT X-ray observatory in the $0.1-2.4$ keV energy range (Trümper 1982). It was not until almost 30 years later that an all-sky X-ray survey was to be carried out again with the SRG/eROSITA X-ray mission. Between December 2019 and December 2021 four all-sky surveys were completed. The sensitivity of eROSITA at soft energies (≈0.1 keV) is not as good as ROSAT's but a larger effective area makes up for this. Only the hotter isolated white dwarfs (T_eff > 20000 K) are observed in X-rays.

Taking the current cumulative eROSITA all-sky data from the surveys $1-4$, which are limited at lower energies to 0.2 keV, and determining the hardness ratios we found about 35000 soft sources with ((0.5keV-2.3keV) − (0.2keV-0.5keV))/((0.2keV-0.5 keV)+(0.5keV-2.3keV))= −1. From this sample about 700 have matches with the Gaia white dwarf catalogue (Fusillo et al. 2021) and about 300 have a probability of more than 80 percent to be a white dwarf. To improve these findings eROSITA data will be processed to a lower energy limit of about 0.1 keV, in order to create a flux limited sample of isolated white dwarfs observed with eROSITA.

The population of high-mass X-ray binaries in the LMC detected during the first eROSITA all-sky survey

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The Magellanic Clouds are our closest star-forming galaxies with low Galactic foreground absorption. This makes them a unique laboratory to study the population of high-energy sources. The SMC hosts a large population of Be/X-ray binaries associated with high star formation activity 25-40 Myr ago. It has been proposed that the HMXB population in the LMC is associated with more recent star formation. However, due to the large angular extent and resulting insufficient coverage of the LMC, this association with SFR is not well established yet.

An essential asset for studying the HMXB population in the entire LMC was the launch of eROSITA. eROSITA scans the sky in great circles crossing at the ecliptic poles. Due to the vicinity of the south-ecliptic pole, sources in the LMC are monitored for up to several weeks during each all-sky survey, leading to a deep total exposure and the possibility of studying long-term temporal behaviour. This allowed us to discover several new HMXBs, verify candidate HMXBs and construct a complete, flux-limited catalogue. During my presentation, I will first focus on HMXB population properties in the LMC. Then I will discuss individual systems we discovered with eROSITA, such as a Be-WD and an SFXT candidate.

The population of X-ray binaries in the Magellanic system detected during the eROSITA all-sky survey

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The Magellanic Clouds are our closest star-forming galaxies with low Galactic foreground absorption and well determined distances making them a unique laboratory to study the population of high-energy sources. The SMC hosts a large population of Be/X-ray binaries associated with high star formation activity 25-40 Myr ago. The HMXB population in the LMC is associated with a star formation period at an earlier epoch and a lower HMXB formation efficiency. The Magellanic Bridge (MB) is thought to be a product of the tidal interaction between the LMC and SMC. It contains both gas and stellar components, with young stellar components (HMXBs) which is thought to have formed in situ, as well as on older population of stars mostly stripped from the SMC by the LMC. The recent eROSITA all-sky survey marks the first comprehensive X-ray coverage of the entire Magellanic system. Proximity to the south-ecliptic pole facilitates extended monitoring of LMC sources during each survey, enabling a deep total exposure and the exploration of long-term temporal behavior. This presentation will unveil the findings from our study of the X-ray binary population across the entire Magellanic system including unique discoveries like X-ray burster in the MB and an ultra-compact binary system.

Studying the signatures of different physical processes on the X-ray luminosity function of high-mass X-ray binaries

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The ever-expanding observational sample of X-ray binaries (XRBs) makes them excellent laboratories for constraining binary evolution, for example, by comparing their X-ray luminosity functions (XLFs) to synthetic XLFs. We study high-mass X-ray binaries (HMXBs) and the effects on their XLF of various, poorly constrained physical assumptions, such as the common-envelope phase, core collapse, and wind-fed accretion. Using POSYDON, we generated 96 synthetic XRB populations corresponding to different combinations of model assumptions. The generated XLFs are feature-rich, deviating from the commonly assumed single power law. We find a break in our synthetic XLF at luminosity 10^{38} erg/s, similar to observed XLFs. However, we find a general overabundance of XRBs (up to a factor of 10 for certain parameter combinations) driven primarily by XRBs with black holes. We find that less well-studied assumptions regarding the circularization of the orbit at the onset of Roche-lobe overflow and asymmetric supernova kicks can impact our synthetic XLFs and reduce the discrepancy with observations. While some model parameters leave distinct imprints on the shape of the synthetic XLFs, others do not have a significant effect overall. Our study reveals the importance of large-scale parameter studies, highlighting the power of XRBs in constraining binary evolution theory.

EXTraS-ordinary Discoveries: Unveiling 60 New Pulsating X-ray Sources with XMM-Newton

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We present the discovery of 62 novel X-ray pulsating sources identified through a comprehensive temporal analysis, spanning more than two decades of *XMM-Newton* observations within the framework of the EXTraS initiative, including subsequent screenings post-EXTraS. Our discovery involved conducting over 10 million fast Fourier transforms on over half a million X-ray source identifications from the *XMM-Newton* archives and utilization of the 3XMM catalog. The exploration encompassed the entire energy spectrum (0.15 – 12 keV) and exploited the maximum available temporal resolution in each *XMM-Newton* public observation up to 2022. Each identification underwent at least one Fourier transform, and for those with sufficient statistical data, a peak-detection algorithm was applied to assess the power spectra, thereby identifying potential significant signals. Most of the discovered signals correspond to spin, or orbital periods of neutron stars and white dwarfs in accretion. This discoveries represents the outcome of the most extensive systematic quest to date for coherent X-ray signals.

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