# Black Hole Accretion Under the X-ray Microscope

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# ABSTRACT BOOK

**Oral Communications and Posters**

Edited by

Simone Migliari

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# Chapter 1

# Invited Speakers

**X-ray quasi-periodic eruptions: where do we stand?**

Riccardo Arcodia[1]
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Quasi-Periodic Eruptions (QPEs) are a new fascinating type of high-energy transients related to black hole accretion, showing high-amplitude bursts of X-ray radiation recurring every few hours. So far only a handful of such sources has been found, originating from the central massive black holes in the nuclei of low-mass galaxies. I will present an overview of their multi-wavelength observational properties and I will also discuss a few possible scenarios for their origin. I will focus particularly on results coming from our blind search with the eROSITA X-ray telescope, which is scanning the X-ray sky and provides the only current systematic method to find more QPEs.

**Shedding light on powerful disk winds**

Valentina Braito[1,2], James Reeves[1,2], Paola Severgnini[3], Gabriele Matzeu[4]
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Over 2 decades ago, X-ray observations revealed the presence of blue-shifted iron K absorption features in the spectra of nearby AGN. These indicated the presence of powerful ultra-fast outflows, with velocities up to 0.3c, launched from the innermost regions of the accretions disk. Systematic studies then showed that these disk winds are present in 40% of the nearby AGN and may be connected to the outflows that are seen on large scales in the host galaxies. Recently, tailored X-ray observational programs on the best examples of these disk winds are shedding more light on their nature and driving mechanisms. At the same time, we are increasing the sample of powerful disk wind with deep ALMA observations to understand whether the disk wind have indeed an effect on the large scale cold ISM. Here I will review our recent results obtained thanks to XMM & NuSTAR observations of the prototypes of the most powerful disk winds focusing on the importance of variability studies.

**AGN UV/optical variability and its (dis)connection to X-rays**

Edward Cackett[1]
[1] *Wayne State University, Detroit, Michigan, USA*

Results from recent intensive multiwavelength continuum reverberation mapping campaigns have posed challenges to the standard picture where variable X-rays irradiate an optically thick, geometrically thin accretion disk driving variations at longer (UV/optical) wavelengths. A common result is that the X-rays correlate more poorly with the UV variations than the UV does with the optical, and in some cases show no correlation at all. In this talk I will review recent observational results and discuss the challenges they present regarding the origins of UV/optical variability in AGN.

**The quest for dual and binary supermassive black holes**

Alessandra De Rosa[1]
[1] *INAF/IAPS*

Hierarchical models of galaxy formation predict that galaxy mergers represent a key transitional stage of rapid SMBH growth; however, the lack of a census of AGN pairs over cosmic time prevents us from firmly connecting AGN triggering and merging processes. The quest for pairs of SMBHs at the dawn of the multi-messenger era is compelling. These systems represent the natural precursor to coalescing SMBHs that are among the loudest sources of gravitational waves. Detecting dual AGN – active SMBHs at projected separations larger than several parsecs – and binary AGN – active SMBHs bound in a Keplerian binary – is an observational challenge. The talk will review the observational efforts, across the electromagnetic spectrum, on the detection and study of dual and binary SMBHs and will reflect on broader implications of these findings when considering the current simulations of merging BH.

## X-ray binary outflows

Maria Diaz Trigo[1]
[1] *ESO*

Absorption lines in the X-ray spectra of X-ray binaries were first detected more than two decades ago with ASCA and identified with a highly ionised plasma from the accretion disk surrounding the compact object (a black hole or neutron star). The high energy gratings aboard Chandra and XMM-Newton enabled to discover such lines in additional sources and to measure blueshifts, indicating the presence of winds. In the past years, the focus has shifted to trying to understand the origin of the winds and quantifying their impact in the evolution of accretion outbursts and the environment of the X-ray binaries.

In this talk, I will review the past observations and what we have learnt from them and the capability of upcoming instrumentation such as the Resolve calorimeter aboard XRISM to answer the still standing questions.

## An overview of accretion physics round black holes

christine done[1]
[1] *University of Durham, UK*

I will review the physics of the accretion flow round black holes across the mass scale, from the stellar mass black hole binaries in our own galaxy to the supermassive black holes in AGN. The stellar mass systems show a distinct spectral transition between the thermal high /soft state to the Compton dominated low/hard state, requiring a change in geometry as well as emission mechanism. The nature of this change is still controversial, but broad band spectra and variability properties all fit well with models where the inner disc is truncated, replaced by a hot flow, though this is challenged by detailed fits to the reflection/iron line. Supermassive black holes show a similar continuum spectral transition in changing look AGN, and I will show that this also can be best interpreted in terms of a truncated inner disc and how the similar issues with iron line/reflection spectra are resolved using the intensive UV/X-ray monitoring campaign data.

**The Athena observatory and its science objectives**

Matteo Guainazzi[1]
[1]*European Space Agency*

In this talk I will present the scientific objectives of Athena, the future X-ray observatory of ESA designed to address the following two questions: a) How does ordinary matter assemble into the large-scale structures we see today? and; b) How do black holes grow and shape the Universe? It will achieve these goals by studying a wide range of astrophysical phenomena, among them: feedback by active galactic nuclei; the formation and early growth of black holes; and the accretion by super-massive black holes through cosmic time, among others. The Athena payload an X-ray telescope with a focal length of 12 m, a 5" angular resolution (Half Energy Width) and an effective area of $\simeq$1.4 square meters at 1 keV, and two instruments: an X-ray Integral Field Unit (X-IFU) for spatially-resolved, high spectral resolution ($\simeq$2.5 eV) imaging spectroscopy over a $\simeq$5" effective diameter field-of-view, and a Wide Field Imager (WFI) for high count rate, moderate resolution spectroscopy over a large field of view ($\simeq$40'x40'). Together with a rapid response of the spacecraft to serendipitous events ($\leq$4 hours over a 50 percent field-of-regard), they pose Athena as a community-driven observatory capable of achieving breakthrough results in almost every field in astrophysics.

**Overview of spectral-timing techniques**

Adam Ingram[1]
[1]*Newcastle University*

Spectral-timing techniques enable us to measure rapid spectral variability of the X-ray signal from accreting black holes. The causal information that this provides is a powerful diagnostic of the accretion flow, and can be used to measure the mass and spin of the black hole itself and even the distance to the system. I will review the main techniques used. The primary tool is the cross-spectrum between the count rate in several energy bands and a common reference band. The modulus of the cross-spectrum identifies the correlated variability amplitude and the argument identifies the time lag between variations in different energy bands. I will review the main uses such as X-ray reverberation mapping and tomographic mapping, and describe the insights that these techniques have recently enabled.

## Extreme Accretion Events: Stellar Tidal Disruption Events (TDEs) and Changing-Look AGN

S. Komossa[1]
[1] *Max-Planck-Institut fuer Radioastronomie, Auf dem Huegel 69, 53121 Bonn, Germany*

Stars approaching a supermassive black hole (SMBH) too closely can be tidally disrupted and accreted. These tidal disruption events (TDEs) were first discovered in the X-ray regime where they appear as luminous, giant-amplitude flares from inactive galaxies. While the majority of X-ray TDEs has been identified from *quiescent, inactive* galaxies and some show the highest amplitudes of variability so far recorded from galaxy cores (amplitudes up to $>$ several 1000), a small fraction of active galactic nuclei (AGN) has been found to be highly variable, too (amplitudes up to $>$100). In AGN, this so-called "changing-look" phenomenon often comes with a strong change in the broad emission lines, leading to Seyfert-type changes between class 1 and class 2.

These two forms of activity represent the extremes of variability among active and quiescent galaxies, and have opened up a new window on understanding accretion physics under extreme conditions. This talk provides a review of the field, with emphasis on the important XMM-Newton contributions to this topic.

## First results from IXPE

Giorgio Matt[1]
[1] *Roma Tre University*

The Imaging X-ray Polarimetry Explorer (IXPE) was launched on December 9, 2021, reopening, after more than 40 years, the polarimetric window in the classical X-ray band. In this talk I will describe the main IXPE characteristics, discuss science prospects for black hole accretion studies, and report on first results.

**Ultraluminous X-ray sources - news and views**

Matthew Middleton[1]
[1] *University of Southampton*

In the last ten years, observations have confirmed beyond doubt that ultraluminous X-ray sources (ULXs) provide an unparalleled view of super-Eddington accretion in action. ULXs are therefore key objects for testing our theoretical understanding of accretion at extreme rates. Much time is now spent on hunting for the elusive signatures of neutron star ULXs, constraining or estimating their magnetic field strength, and exploring how the numbers of observed systems might relate to the underlying population. Other areas of intense effort include locating and probing the sub-relativistic winds revealed in the X-rays, exploration of the vast bubble nebulae surrounding them, locating the donor stars and exploring new theoretical means to locate black hole ULXs (which are even more elusive than neutron stars!). In this overview, I will discuss recent discoveries and theoretical developments, the impact of new observations by next-generation instruments, and how we can use the opening of the transient sky to learn more about the population.

**Imaging a supermassive black hole**

Luciano Rezzolla[1]
[1] *Goethe Universität, Frankfurt, Germany*

I will briefly discuss how the first image of a black hole was obtained by the EHT collaboration. In particular, I will describe the theoretical aspects that have allowed us to model the dynamics of the plasma accreting onto the black hole and how such dynamics was used to generate synthetic black-hole images. I will also illustrate how the comparison between the theoretical images and the observations on a broad range of frequencies has allowed us to deduce the presence of a black hole in M87 and to extract information about the accretion process. Finally, I will describe the lessons we have learned about strong-field gravity and alternatives to black holes.

**1ES1927+654: a new type of changing-state AGN**

Claudio Ricci[1], Erin Kara[2], Mike Loewenstein[3], Benny Trakhtenbrot[4], Iair Arcavi[4]
[1] *Universidad Diego Portales, Chile*
[2] *MIT, USA*
[3] *NASA, USA*
[4] *Tel Aviv University, Israel*

Accreting supermassive black holes are known to show variable optical, ultraviolet and X-ray emission. One of the most intriguing aspects of this behaviour is associated with changing- look or changing-state sources, in which the optical/ultraviolet broad emission lines, produced by rapidly-moving material surrounding the SMBH, appear or disappear.

In my talk I will discuss the drastic transformation of the X-ray properties of a nearby active galactic nucleus (AGN), following a changing-look event. After the optical/UV outburst the power-law component, produced in the X-ray corona, completely disappeared, and the spectrum became dominated by a blackbody component, similar to what is observed in tidal disruption events. Such a phenomenon was never observed before, and the disappearance of the hard x-ray emission implies that the X-ray corona, ubiquitously found in AGN, was destroyed in the event. I will discuss the results of our X-ray monitoring campaign of this source, and how this extreme event could be explained by a tidal disruption event in an accreting supermassive black hole.

**Accretion driven jets in X-ray binaries**

Alexandra Tetarenko[1]
[1] *Texas Tech University*

One of the key open questions in high-energy astrophysics is understanding the complex relationship between the accretion flow and the launching of relativistic jets from compact objects. X-ray binaries are ideal test-beds to study this relationship as they evolve on rapid timescales, entering into bright out-bursting periods where we can track changes in the accretion flow and jet in real-time for a single system. In this talk, I will review our current understanding of the connection between the properties of jets (kinetic power, time variability, particle acceleration, polarization, mass outflow rate) and the accretion flow (geometry, mass inflow rate, radiative power) in X-ray binaries, highlighting the latest results in the field, as well as advances to observing techniques, instrumentation, and analysis/computational tools that are leading to new discoveries. Additionally, I will discuss the key role that new (e.g., JWST, MeerKAT) and next-generation (e.g., ngVLA, SKA, ngEHT) instruments will play in advancing our understanding of these jets.

# Chapter 2

# Extreme variability events

### Measuring the mass and the spin of intermediate-massive black hole candidates using tidal disruption events

Zheng Cao[1,2], Peter Jonker[1,2], Sixiang Wen[2], Nicholas Stone[3], Ann Zabludoff[4]
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[3]*Racah Institute of Physics, The Hebrew University*
[4]*University of Arizona*

A star can be tidally disrupted by a black hole as a tidal disruption event (TDE), triggering various transient electromagnetic signals in the optical/UV/X-ray band. The number of TDEs observed is rapidly increasing in recent years thanks to large surveys and advanced detectors. In this talk, I will discuss the effort of implementing X-ray TDE observations of the XMM-Newton Satellite to measure the mass and the spin of the host black hole, which provides unique opportunities to find intermediate-massive black holes (IMBHs). I will highlight the key results of several TDE analyses obtained. By modelling the high/super-Eddington accretion disc in TDEs with a state-of-art slim disc model, we are able to explain the X-ray spectra of TDEs and find several fast-spinning IMBHs with masses ranging from $10^4$ to $10^6$ solar mass. With the expectation of a soaring number of TDE detections in the coming years, I will discuss the potential impact of TDE modelling on constraining the existence and properties of an IMBH population, which is critical to test black hole evolution theories.

### X-Ray Observations of Tidal Disruption Event ASASSN-14li

Suyog Garg[1,2], Dheeraj Pasham[3]
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Tidal Disruption Events (TDEs) are catastrophic events in which an otherwise dormant Super-Massive Black Hole tidally disrupts a star passing too close to it. TDEs happen roughly once every ten thousand years. The process leads to the formation of an accretion disk and produces a bright transient flare. As gas from the accretion disk falls into the black hole, a collection of ultra-hot gas particles gets formed powered by the magnetic field. This collection of particles emits in X-Ray and is called the X-Ray corona. X-Ray corona are ubiquitously found in Active Galactic Nuclei and are a feature of TDEs. Studying corona formation is important in order to understand how accretion disks evolve. At 90 mega-parsec ASASSN-14li is one of the nearest tidal disruption events. Consequently, it has been famously observed in multiple wavelengths amounting to a huge corpus of observational data. XMM-Newton has observations of ASASSN-14li starting from 2014. In this work, we present some preliminary results relating to the corona formation in ASASSN-14li. X-Ray corona have also been found to disappear. It will be interesting to see how ASASSN-14li has evolved over half a decade of observations.

**The enigmatic X-ray quasi-periodic eruptions of RX J1301.9+2747**

Margherita Giustini[1]
[1] *Centro de Astrobiología (CAB, CSIC-INTA)*

RX J1301.9+2747 is the second galaxy where X-ray quasi-periodic eruptions (QPEs) have been detected, and the only one where QPEs have been observed for more than twenty years. The latest X-ray and radio observational campaign, performed in July 2020, gave enigmatic results. Contrary to the discovery source GSN 069, where the quasi-periodicity of the QPEs is striking, the QPEs in RX J1301.9+2747 are spaced by a non-immediately discernible repetition pattern. Furthermore, the long XMM-Newton observation (one full revolution) revealed the presence of two much lower-amplitude QPEs, as well as hints of alternating softer and longer/harder and shorter QPEs. The VLA radio exposure covered only a short segment of the X-ray light curve and nonetheless delivered promising results in terms of possible correlated X-ray and radio emission. I will compare these results to the observed properties of the other four known QPE sources, and I will discuss them in the context of the possible physical scenarios able to explain the QPE phenomenology.

**Multi-wavelength follow-up of extreme variability in galactic nuclei detected with eROSITA**

David Homan[1], Mirko Krumpe[1], Alex Markowitz[2], David Buckley[3], Stefano Ciroi[4], Francesco Di Mille[5], Mariusz Gromadzki[6], Saikruba Krishnan[2], Tathagata Saha[2], Malte Schramm[7], Joern Wilms[8]
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[5] *Carnegie Institution of Washington*
[6] *Astronomical Observatory, University of Warsaw*
[7] *Saitama University*
[8] *University of Erlangen-Nuremberg*

The eROSITA all sky X-ray survey has provided the basis for a large-scale search for extreme X-ray variability in extragalactic objects, associated with accretion changes in supermassive black holes. We have combined the survey data-set with a multi-wavelength follow-up campaign of the most variable objects, including optical spectroscopy, and X-ray and UV observations. This presentation will cover the results of our search covering the first two years of eROSITA's operation, consisting of four X-ray epochs for each object. I will introduce our sample of extremely variable source by detailing our selection methods. In total our sample consists of ~2,000 vetted sources, of which approximately 10 percent have additional follow-up data and at least one follow-up optical spectrum. I will provide a brief overview of some of the most interesting sources detected (extreme flaring and accretion shutdown candidates around supermassive black holes). Finally, I will discuss our results in the context of the link between extreme X-ray and optical variability, specifically 'changing-look' behaviour in AGN, and the time-scales involved in large scale accretion changes around SMBHs.

### Repeating X-ray and UV flares in the changing-look AGN Mrk 590

Daniel Lawther[1]
[1]*Steward Observatory, University of Arizona, Tucson, AZ, USA*

Mrk 590 'turned off' around 2012, losing its broad emission lines and nuclear continuum. Since 2017 it has partially re-ignited and is now in a repeat flaring state near an Eddington luminosity ratio of 1%. We find that the X-rays are unusually highly correlated with the UV variability, with a 3-day X-ray to UV delay, inconsistent with the standard 'lamp-post' reprocessing model with the X-ray source and inner disk both located near the central black hole. I will present the reverberation and timing properties of Mrk 590 during these flares, and discuss possible explanations for the observed activity. I will also discuss the long-term variability of the soft X-ray excess, both in the previous turn-off state and during the recent flares. In the context of the evolution of the overall spectral energy distribution, the soft excess variability provides clues as to the nature of the changing-look transition in Mrk 590.

### Deciphering the extreme X-ray variability of an eROSITA discovered nuclear transient

Zhu Liu[1], Iuliia Grotova[1], Adam Malyali[1], Arne Rau[1], Andrea Merloni[1], Mirko Krumpe[2], David Homan[2]
[1]*Max Planck Institute For Extraterrestrial Physics*
[2]*Leibniz Institute for Astrophysics Potsdam*

During its four year all-sky survey, SRG/eROSITA has uncovered a large sample of X-ray transients associated with the nuclei of galaxies which show no obvious signatures of prior AGN activity. In this talk I will highlight an exceptional event found in the second eROSITA all-sky survey. eRASSt J045650-203751 (hereafter J0456-20) is an extremely variable nuclear transient discovered by SRG/eROSITA in a quiescent galaxy at redshift of $z \sim 0.077$. The X-ray luminosity peaked at a 0.2-5.0 keV luminosity of 1.2E44erg/s and then dropped drastically by a factor of $> 1000$ within 2 weeks. Following a second rise phase, this rapid X-ray drop occurred again about 227 days later, suggesting J0456-20 as a likely repeated nuclear transient. A repeated behavior was also detected in the UV. QPOs with periods of 4166s and 25000s have been detected at 3 confidence level from two XMM-Newton observations respectively, indicating that the inner radius of the accretion disc may be close to the innermost stable circular radius (ISCO). We discuss the scenario that the X-ray/UV variability of J0456-20 is caused by a repeated partial tidal disruption event (TDE), while the drastic X-ray flux drops are due to accretion state transitions.

### Multi-wavelength follow-up of an extremely luminous, eROSITA-selected tidal disruption event candidate

Adam Malyali[1], Arne Rau[1], Zhu Liu[1], Andrea Merloni[1], Iuliia Grotova[1], David Homan[2], Mirko Krumpe[2]
[1]*Max Planck Institute for Extraterrestial Physics*
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During its four year all-sky survey, eROSITA is discovering a large sample of X-ray selected stellar tidal disruption event (TDE) candidates. These events, which result in the formation of a nascent, compact accretion disk around the black hole, see the accretion rate transition from being effectively quiescent, to super-Eddington, and back to sub-Eddington, over timescales of months to years; they therefore represent unique probes of accretion physics onto black holes. In this talk, I will present results from our  400 day multi-wavelength follow-up campaign of an extremely luminous TDE candidate discovered by eROSITA during its second all-sky survey. Following the eROSITA detection, the source has been extensively followed-up by Chandra, NICER, Swift and XMM observations, showing a net fading in X-ray flux by over two orders of magnitude. During the early stages of the outburst, these observations also reveal large amplitude modulations of the soft X-ray emission, which are not detected in observations performed several months later. Lastly, I will discuss possible physical interpretations of such extreme variability, and how general relativistic effects may have shaped the evolution of this TDE.

### Probing Extreme Accretion Physics with X-ray Nuclear Transients

Megan Masterson[1], Erin Kara[1]
[1]*Massachusetts Institute of Technology, Cambridge, MA, USA*

Recent discoveries of extreme accretion events around supermassive black holes are defying what we thought we knew about active galactic nuclei and the accretion process. These transients are being discovered in ever-increasing numbers, but the X-ray emission, despite probing the innermost regions of the accretion flow, is still poorly understood. Advances in high-cadence, high-throughput X-ray observations with NICER have greatly improved our ability to probe the evolution of the inner accretion flow dynamics and geometry in X-ray nuclear transients. In this talk, I will present detailed X-ray spectral modeling of the evolution of a sample of tidal disruption events (TDEs) and other X-ray nuclear transients observed with NICER and XMM-Newton. Using a new soft reflection model called xillverTDE, we capture the evolution of the dynamics, geometry, and composition of the accretion flow and subsequent ejecta. I will highlight how this modeling has greatly improved our understanding of the extreme X-ray nuclear transient in 1ES 1927+654 and show how applying this model to a larger sample of nuclear transients helps constrain theories for the variety of X-ray emission from TDEs.

### A multi-instrument look at archival variable AGNs

Erwan Quintin[1], Natalie Webb[1]
[1] *IRAP, Toulouse*

The last three decades have seen the launch of numerous X-rays observatories, providing a long temporal baseline to use to search for long term transients. In order to take full advantage of this large amount of available data, we have developed a systematic study of the cross-correlation of different X-rays source catalogs using XMM-Newton, Chandra, Swift, ROSAT and early eROSITA data. Our method also takes into account multi-instruments upper limits in the case of non-detections. Finally, we enhanced this catalog by using complimentary multi-wavelength data to select extra-galactic sources.

This method allows to unveil long-term X-ray variability of both flux and spectral shape of a large number of serendipitous sources, which enables a systematic search for some of the most puzzling variable events in AGN accretion, from Changing Look AGNs to Tidal Disruption Events. Additionally, this method is expected be embedded into the XMM-Newton pipeline in the form of a trigger system, to alert the community in quasi real time to such events. We will present here some early archival results and statistics obtained from our method, some of the most interesting candidates found, as well as its anticipated outcome as a real-time alert system.

### Fully relativistic global hydrodynamics simulation of tidal disruption event

Taeho Ryu[1], Julian Krolik[2], Tsvi Piran[3], Scott Noble[4], Mark Avara[5]
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[5] *Cambridge University, Cambridge, UK*

Approximately 100 tidal disruption event candidates have been observed so far. In the near future, the number will grow dramatically with detections by the ongoing and upcoming surveys (e.g., eROSITA and LSST). However, the mechanism responsible for the luminosity and the shape of the light curve of observed events is poorly understood. For reliably classifying transients and deciphering their emission features to unveil the nature of the main source and surroundings, it is crucial to understand the dominant emission mechanisms of the events. The only way to fully investigate the long-term evolution of the debris and the emission mechanism is to perform global simulations with astrophysically realistic initial conditions. However, performing such simulations had been considered almost impossible because of very high computational costs. Using an innovative numerical technique that I have developed, I am currently performing a fully relativistic global hydrodynamics simulation with realistic initial conditions and investigating the emission mechanism. I will present the results from our simulations and discuss their implications.

**Searching for overlooked TDEs in the 4XMM catalog**

Andrea Sacchi[1], Guido Risaliti[1,2], Giovanni Miniutti[3]
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[3] *Centro de Astrobiología (CSIC-INTA)*

Tidal disruption events (TDEs) are usually identified thanks to their extreme variability be it in the X-ray or optical/UV band. X-ray detected TDEs are usually characterized by a bright super-soft emission which helps in their identification: apart from few other sources (Hyper-luminous X-ray sources and super-soft AGN) which can be distinguished by their optical emission, no other extra-galactic sources possess such steep X-ray spectra.
Given that TDEs are rare events but large X-ray catalog are available, we searched for super-soft sources which could represent overlooked TDEs in the 4XMM catalog.
In this talk I will present our method and results: we identified 4 convincing TDE candidates thanks to their spectral shape, optical counterpart and variability, which in one case we assessed with an XMM follow-up observation. If confirmed these sources would be the first TDEs discovered by their spectral features rather than their transient nature.

**Tidal disruption events and quasi periodic eruptions**

Natalie Webb[1]
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Tidal disruption events (TDEs) occur when a star passes close to a massive black hole, so that the tidal forces of the black hole exceed the binding energy of the star and cause it to be ripped apart. Part of the matter will fall onto the black hole, causing a strong increase in the luminosity. Such events are often seen in the optical or the X-ray (or both) or even at other wavelengths such is in the radio, where the diversity of the observed emission is still poorly understood. The XMM-Newton catalogue of approximately a million X-ray detections, covering 1239 square degrees of sky, contains a number of these events. Here I will show the diverse nature of some of the TDEs discovered in the catalogue and discuss how they can help us understand the growth of supermassive black holes, as well as their relationship with quasi periodic eruptions.

### Host galaxy properties of quasi-periodically erupting X-ray sources

Thomas Wevers[1], Dheeraj Pasham[2]
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Quasi-periodic X-ray eruptions (QPEs) are a recently discovered phenomenon, the nature of which remains unclear. Based on their discovery in active galactic nuclei (AGN), explanations related to an AGN accretion disk, or potentially stellar tidal disruption event (TDE), were put forward. Alternatives including highly unequal mass compact object binaries have also been proposed to explain their properties. In this contribution we present new results from a systematic study of the five known QPE host galaxies, with the aim of providing new insights into their nature. We analysed new and archival medium resolution optical spectroscopy of the QPE hosts, measuring emission and absorption line fluxes and ratios to locate the hosts on diagnostic diagrams. We found evidence for an AGN in all QPE hosts; inferred low black hole masses; and revealed a significant over-representation of quiescent, Balmer strong (post starburst) galaxies among the QPE hosts. We will discuss our results in the context of other transients (such as tidal disruption events), and the implications for theoretical scenarios proposed to explain the QPE phenomenon.

### Accretion state changes in a supermassive black hole following a tidal disruption event

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Following a tidal disruption event (TDE), the accretion rate can evolve from quiescent to near-Eddington levels and back over timescales of months to years. This provides a unique opportunity to study the formation and evolution of the accretion flow around supermassive black holes (SMBHs). We present an extensive dataset spanning 2 years of multi-wavelength monitoring observations of the TDE AT2018fyk at X-ray (including XMM-Newton, Chandra, Nicer and Swift), UV, optical, and radio wavelengths. Using the evolution of the X-ray spectral and timing properties, as well as the UV to X-ray spectral slope, we identify three distinct accretion states and two state transitions between them. We will present the observations and discuss the accretion flow properties and evolution, highlighting similarities and differences with stellar mass black hole accretion states.

# Chapter 3

# BH X-ray binaries and ULXs

**Investigation of The Connection Between X-ray Binaries and Compact Star Clusters in NGC 628**

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We search a possible connection between the types of X-ray binaries (XRBs) and properties of compact star clusters in the nearby galaxy NGC 628. Using Chandra archival data covering the years 2000-2018, 75 X-ray sources are detected within the field of view of observations. A total of 69 XRBs, one of which is an ultraluminous X-ray source (ULX), have been defined in the luminosity range of $L_X = 10^{36-39}$ erg $s^{-1}$. We also identify the optical counterpart(s) of 15 of the 44 XRBs that coincide with the HST field of view via improved astrometry. We classify 15 of them as HMXBs based on the presence of optical counterparts of XRBs. The remaining sources with no optical counterparts are classified as LMXBs. We also search compact star clusters in this galaxy from the multi-band optical images drawn from HST archives. 860 compact star cluster candidates were identified and their ages and masses determined by applying the best-fit SSP (Simple Stellar Population) model to their color-color diagram. We note that in NGC 628, HMXBs are associated with younger star clusters and LMXBs with older ones.

**Properties of the type-C quasi-periodic oscillations of MAXI J1348-630 using NICER**

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At the end of 2019 the X-ray source MAXI J348-630 went into outburst, transiting over all the canonical source states of a black-hole transient. After the main outburst, MAXI J1348-630 showed several reflares during which the source remained in the low/hard state. The source was observed with NICER on an almost daily basis from the beginning of the outburst and during the reflares. We used these data to study the type-C quasi-periodic oscillation (QPO) detected during the main outburst and the first reflare. We show that, during the reflare, the properties of the type-C QPO are similar to those of type-C QPOs observed in other sources during the main outburst, which suggests that the mechanism that produces these QPOs is the same in both cases. We fitted the energy-dependent fractional rms amplitude and phase lags of the type-C QPO in MAXI J1348-630 using the time-dependent Comptonisation model of Karpouzas et al. (2020) with the addition of Bellavita et al. (2022) that considers an accretions disc instead of a blackbody as the source of seed photons. We used these fits to study the evolution of the properties of the Comptonising region that produces the QPO during the whole outburst and reflare.

**Optical Counterparts of ULXs in NGC 1672**

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In this study, we deploy archival data from HST, Chandra, XMM-Newton, and Swift-XRT, to probe the nature of 9 candidate ULXs in NGC 1672. Specifically, our study focuses on using the precise source positions obtained via improved astrometry based on Chandra and HST observations to search for and identify potential optical counterparts for these ULXs. Unique optical counterparts are identified for two of the ULX candidates i.e., X2 and X6; for three of the candidates i.e., X1, X5 and X7, we found two potential counterparts for each source within the respective error radii. No optical counterparts were found for the remaining four sources. We used colour magnitude diagrams (CMDs) to investigate ages and masses of the counterparts. The estimated masses of the donors fall in the range (6-20)$M_\odot$ which would suggest a high-mass X-ray binary classification for these sources. Of all the sources studied, X9 exhibits the most variability whereby the X-ray flux varies by a factor of $\sim 50$ over a time period spanning 2004 to 2019, and also traces a partial q-curve-like feature in the hardness-intensity diagram, hinting at possible spectral transitions.

**Long-term X-ray variability of the ULX M81 X-6: black hole or neutron star accretor?**

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Ultraluminous X-ray sources (ULXs) are unique super-Eddington stellar-mass black hole/neutron star (BH/NS) accretors. Constraining their BH-to-NS population ratio could shed light on the physics of super-Eddington accretion and on the cosmic history of massive star binary evolution. When no pulsation is detected, hints on the nature of the compact objects can be retrieved from studying the long-term, X-ray variability. To this aim, we analysed archival Chandra, Swift/XRT, and XMM-Newton data of the ULX M81 X-6 over the last decade, investigating its spectral evolution, timing properties, and temporal track on the Hardness-Intensity diagram. We found that the source oscillates between two main states: one harder and more luminous, the other softer and less luminous, a behavior similar to at least one pulsating ULX, NGC 1313 X-2. We infer that the system is seen at low inclination angles, while the two different states might be due to either disc precession or to a change in the mass accretion rate, resulting in variations of the local absorption and of the temperatures of the innermost and outermost parts of the disc. We show that this analysis can be a powerful tool to discern the nature of the accretor in ULXs.

### Variability in tilted, truncated discs around black holes

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Many accreting black holes and neutron stars exhibit rapid variability in their X-ray light curves termed quasi-periodic oscillations (QPOs). Low-frequency, Type-C QPOs, observed especially during the low/hard state are thought to originate from the Lense-Thirring precession of a hot, geometrically thick, accretion flow misaligned with the black hole spin axis. Earlier numerical works have demonstrated the precession of isolated, tilted, accretion discs at frequencies matching the observations. However, none of the QPO models and simulations account for the surrounding geometrically thin disc. To address the coupling between the outer thin disc and the inner thick flow, we perform GRMHD simulations of a truncated disc with the inner hot flow misaligned with the black hole spin axis. We find that the presence of the outer thin disc slows down the precession of the inner hot flow. The misalignment also excites variability in the inner hot flow, which is otherwise absent in the aligned discs. Lastly, using these simulations, we also attempted to study how the precession of the inner torus affects the emission of the Fe K lines from the outer thin disc using CLOUDY photoionization simulations accounting for realistic line profiles and spectra generated from our GRMHD simulations.

### The inner flow geometry in MAXI J1820+070 during hard and hard-intermediate states

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Black hole X-ray binaries (BHXRB) show complex, non-stationary behaviour during an outburst, characterized by significant changes of their spectral and timing properties. The origin of such behaviour is currently unknown, although evolution of the geometry of the innermost accretion flow is thought to play a major role. We tackled the problem of constraining the changes in the geometrical structure of the accretion flow in hard and hard-intermediate states, and during the transition to the soft-intermediate state. To this aim we studied NICER data of the exceptionally bright BHXRB system MAXI J1820+070, using different X-ray spectral-timing methods. We report results showing evidences of a steady evolution of the inner radius of the disc, accompanied by major changes in the structure of the X-ray source at the transition to the soft-intermediate state and possibly related to ballistic jet ejections.

**A comprehensive, Bayesian analysis of X-ray spectra from the black hole LMXB MAXI J1820+070 using XMM-Newton and NuSTAR.**

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The X-ray spectra of accreting black hole LMXBs contain information about the geometry of the accretion flow and potentially the spacetime near black holes. In practice, inferences about spin and inner flow geometry remain controversial despite major improvements in signal-to-noise and resolution of the data. Rather than measure the spin or inner radius from a model with spin or R_in as free parameters, we fit two spectral models – one with spin $a = 0$ and R_in = 6r_g, one with spin $a = 0.998$ and R_in $\sim$ 1r_g – to understand under what conditions these models can reproduce data from LMXB systems. We adopt a fully Bayesian approach with the best available prior information on mass, distance and inclination, the latest and most self-consistent combination of various emission components and the most accurate models of interstellar absorption, from XMM-Newton RGS data. Our test case is the black hole LMXB MAXI J1820+070. We fit data over the 0.8 - 70 keV range using 3 XMM-Newton and 2 simultaneous NuSTAR observations. In future this analysis will be extended to XMM-Newton data on 41 black hole XRBs and over 100 observations, making it the largest and most self-consistent analysis of its nature.

**Evaluating the jet/accretion coupling of Aql X-1: probing the contribution of accretion flow spectral components**

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The coupling between radio and X-ray luminosity is an important diagnostic tool to study the connection between the accretion inflow and jet outflow for low-mass X-ray binaries (LMXBs). Furthermore, the comparison of NS- and BH-LMXBs provides useful information about the role of compact objects in launching jets. Interestingly, studies have shown discrepancies between the radio/X-ray coupling of NS- and BH-LMXB sources. The radio/X-ray correlation for individual NS-LMXBs is scattered, whereas for individual BH-LMXBs a more consistent correlation is generally found. Furthermore, we observe jet quenching for both systems, but it is unclear what exactly causes this, and if jets in NS-LMXBs quench as strongly as those in BH-LMXBs. While additional soft X-ray spectral components can be present for NS-LMXBs due to the presence of the neutron star's surface, disentangling the individual X-ray spectral components has thus far not been considered when studying the radio/X-ray coupling. In this talk, I will present our work on analysing Swift/XRT observations matched with quasi-simultaneous archival radio observations of the 2009 November outburst of Aql X-1. In this study we decompose thermal and Comptonised spectral components in Swift/XRT spectra, discuss whether the presence of additional thermal emission affects the radio/X-ray coupling, and discuss future research.

### Testing the LenseThirring plane for Ultraluminous X-ray sources

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The majority of Ultraluminous X-ray sources (ULXs) are now thought to be powered by super-Eddington accretion onto stellar-mass compact objects. While the detection of X-ray pulsations has established the existence of neutron star (NS)-ULXs, black hole(BH)-ULXs still remain an elusive population, calling for new means to discern between these two accretors. A possible mean might be through the study of their superorbital periods, recently proposed to be due to Lense-Thirring precession of the accretion inflow and outflowing super-Eddington wind. This is because the different physical properties of BHs and NSs, should lead to observable differences in the timescale of their precessing periods as well as the temperature of the photosphere of their outflows. Making use of the extensive Swift-XRT archival data, I will present a systematic study of the lightcurves of a large sample of ULXs (>10) in order to robustly determine the presence of long (> few days) quasi-periodic variability in an effort to, not only test the Lense-Thirring scenario, but also whether it may be possible to use it as a tool to discriminate the nature of the accretor in ULXs. Based on the properties of the superorbital periods (variable and/or transient) I will also discuss alternative scenarios.

### Spectro-Timing analysis of Cyg X-1 with NICER+NuSTAR

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The unprecedented capabilities of NICER allow us to constrain the properties of black hole binaries by combining spectral and timing techniques. We focus our analysis on NICER+NuSTAR data of Cyg X-1 to study the coronal geometry of the innermost region surrounding the black hole. To this end, we apply the new spectral-timing model reltrans to fit NICER data in the hard state. We fit the lag-energy spectra and time-averaged spectrum simultaneously to independently constrain the recently revised black hole mass of 21 solar masses. We aim to constrain the interaction between the corona and inner accretion disk, which is important to shed light on the ongoing debate about the truncation of the inner disk. We also explore the wind properties of HDE 226868 and the relativistic reflection in the accretion disk.

### Multi-wavelength properties of the black hole transient MAXI J1820+070

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The black hole transient MAXI J1820+070 underwent a bright outburst in 2018, and it was followed with XMM-Newton and many other facilities in a comprehensive multi-wavelength campaign. In this presentation we highlight the results of our multi-wavelength campaign of MAXI J1820+070. We cover the detection of X-ray dipping with XMM, as well as our optical polarimetric campaign that allowed us to measure over 40 degrees misalignment between the black hole rotation axis and the axis of the orbit in which companion star orbits around the black hole. We will also discuss the broad band spectral energy distribution of MAXI J1820+070, and the role of the jet in producing the near-infrared and optical emission across its spectral states.

### Modeling energy-dependent aperiodic variability of black hole X-ray binaries

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The nature and geometry of the accretion flow of black hole X-ray binaries in the low/hard state are still controversial. One limitation is that spectral fitting alone is generally degenerate. We add independent information carried by the fast variability from milliseconds to seconds to data analyses. We have developed a timing model based on a propagating mass accretion rate fluctuations scenario, one of the most compelling explanations of the broad-band aperiodic variability. Coupling it with spectral modeling, we have performed a spectral-timing analysis for the black hole binary MAXI J1820+070 observed by NICER, NuSTAR, and Insight HXMT from 0.5 keV to 200 keV. We show how our model captures the broad-band variability properties successfully, including their energy dependence, and how it gives new insight into the structure of the accretion flow close to the black hole.

### Using X-ray Eclipse Mapping to Constrain the Mass of the Black Hole in the X-ray Binary M33 X-7

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X-ray eclipse mapping is a powerful modelling technique capable of constraining the mass of compact objects in eclipsing binaries and probing the outflow from the companion star. In this talk, I will discuss the recent development of our eclipse mapping model and demonstrate its capabilities by presenting our recent work to model the X-ray eclipses of the black hole (BH) X-ray binary system M33 X-7. This system hosts a $\sim 15M_{\odot}$ BH in a slightly eccentric orbit with a $\sim 70M_{\odot}$ companion. We utilise archival Chandra data, which show X-ray eclipses recurring on the orbital period of $\sim 3.45$ days. The companion star's outflow causes some absorption and extends the duration of the ingress and egress. Our modelling probes the density of this outflow, allowing us to infer its extent, ionisation and covering fraction. The properties of this outflow influence the shape of the eclipse profile. Therefore, by including the wind properties in our modelling, we can carefully map the structure of the eclipse profiles and place tight constraints on the duration of totality, binary mass ratio and inclination angle. Combining these constraints with previously measured radial velocity semi−amplitudes thus enables precision measurement of the BH mass.

### A long stare at Hercules X-1: investigating the vertical structure of an accretion disc wind

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Hercules X-1 is an X-ray binary exhibiting a warped, precessing accretion disc. The disc is observed almost edge-on, offering the unique opportunity to study an accretion flow at changing sightlines towards the central source. We previously detected a strongly variable disc wind in Her X-1 using archival datasets. We proposed that the observations sample varying sightlines towards the accretor and thus measure the wind properties at different locations and heights above the disc. In this talk, I will present new results on a recent Large XMM-Newton campaign (380 ks) from August 2020, which sampled a significant fraction of a single precession cycle. The optical depth of the wind absorption lines strongly anti-correlates with the disc precession phase, and thanks to the high-quality observations and detailed photoionization modelling, we determine that this evolution is due to a decrease in wind column density as the precession cycle progresses. This indicates either that the wind is much weaker at larger heights above the disc (sampled at later precession phases), or we are observing it at much larger distances from the X-ray source. I will present these new results on precision tomography of a disc wind and other results from this extremely rich dataset.

### 3D RMHD simulations of microquasar jets: from the binary to the ISM

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In this contribution, we will present a collection of 3D Relativistic Magnetohydrodynamics numerical simulations of microquasar jets, from the interaction with the stellar winds driven by the companion star near the compact object, to the propagation and interaction with the ISM beyond the scale of the binary.

These simulations are performed with our different proprietary codes: Lóstrego, our new computational tool to simulate relativistic magnetized plasmas in three-dimensional cartesian coordinates, and Ratpenat, a three-dimensional hydrodynamical code. Among the most recent upgrades that we have developed, these codes also include a module of atomic hydrogen ionization, high-order spatial and temporal numerical methods and a module of radiation transport to solve the coupled equations of radiation-RMHD.

Using these programs and the available modules, we aim to provide new insights on the physics behind microquasar jets propagation, especially focusing on the role of magnetic fields on jet dynamics, collimation/disruption and long-term stability. We will also analyze the interaction with the ISM in two fiducial cases: Cygnus X-1 and SS433. The results of our simulations help interpret the available observations at all energy wavelengths on the basis of the current theoretical knowledge of these sources.

### The stellar wind in Cygnus X-1: a X-ray spectral-timing view

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High mass X-ray binaries accrete via the stellar wind of their supermassive companion. The stellar wind does not appear as a smooth flow, but it shows strongly dense and highly perturbed regions or clumps. As these clumps cross our line of sight, part of the X-ray emission is absorbed, leading to dipping events in the light curves. We performed an analysis of the long XMM Newton monitoring of the black hole binary Cyg X-1/HDE 226868 during its hard state. This monitoring is part of the CHOCBOX (Cyg X-1 Hard state Observations of a Complete Binary Orbit in X-rays) campaign. In this talk, I will present the latest results on the effects of the stellar wind on the spectral-timing properties of Cyg X-1 for more than one and a half orbital periods. In particular, I will focus on the changes in the intrinsic variability, in the intrinsic coherence and in the time lags due to the presence of the stellar wind.

### Observational Properties of Puffy Accretion Disk

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We have performed general relativistic radiative magnetohydrodynamics (GRRMHD) simulations of stable accretion disks around a stellar-mass black hole with sub-Eddington mass accretion rates. The numerical solutions reveal an elevated vertical structure. Above a dense and geometrically thin core of dimensionless thickness h/r  0.1, resembling a classic thin accretion disc, a puffed up, optically and geometrically thick layer of lower density and h/r  1.0 is formed. We refer to this solution as the puffy disk. We discuss the observational properties of puffy disks, in particular the geometrical obscuration at higher observing inclinations of the inner area by the puffed up region, and collimation of radiation along the accretion disk spin axis. These effects may explain the apparent super-Eddington luminosity of some ultraluminous X-ray binaries. We also present synthetic spectra of puffy disks, and show that they are qualitatively similar to Comptonized thin disk spectra. We demonstrate that the existing XSPEC spectral models provide good fits to synthetic spectra of puffy disks but cannot correctly recover the input luminosity, nor the black hole spin. We suggest that puffy discs may correspond to X-ray binary systems in the intermediate spectral state with luminosities above 0.3 of the Eddington luminosity.

### The Hyperluminous X-ray Source Population

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We have recently published a catalogue of 1843 candidate ultraluminous x-ray sources (ULXs; Walton et al. 2022). This is the largest catalogue of ULXs to date and was built by cross-correlating recent serendipitous source catalogues from the *XMM-Newton*, *Swift* and *Chandra* observatories with a large sample of galaxies, primarily from HyperLEDA. The catalogue contains 71 hyperluminous X-ray source (HLX) candidates, the most extreme members of the ULX population with luminosities above $10^{41}$ erg s$^{-1}$. These sources are often considered the best candidates for IMBH accretors and include the archtypal IMBH candidate ESO 243-49 HLX-1. However, the most luminous of the known pulsating ULXs (PULXs), NGC 5907 ULX, is also a HLX at its brightest. We demonstrate that these two objects occupy distinct areas of parameter space, and use this to attempt to diagnose the nature of 42 HLXs that we select as the best candidates based on their multiwavelength counterparts and X-ray data quality. We will discuss the implications of this work for the nature of HLXs.

**Coupling between the accreting corona and the relativistic jet in the micro quasar GRS 1915+105**

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It has been proposed that the jet in GRS 1915+105 is fed by instabilities of the inner accretion disc. We show that there is a significant correlation between: (1) the radio flux, coming from the jet, and the flux of the iron emission line, coming from the disc and, (2) the temperature of the X-ray corona and the amplitude of a high-frequency variability component, coming from the innermost part of the accretion flow. At the same time, the radio flux and the flux of the iron line are strongly anti-correlated with the temperature of the X-ray corona and the amplitude of this variability component. These correlations persist over 10 years, despite the highly variable X-ray and radio properties of the source in that period. Our findings show that the energy that powers this black-hole system can be directed in different proportions either to the X-ray corona or the jet. When this energy is used to power the corona, raising its temperature, there is less energy left to fuel the jet and the radio flux drops, and vice-versa. These facts, plus our modelling of the variability in this source, suggest that in GRS 1915+105 the X-ray corona turns into the jet.

**Gravitational waves or X-ray counterpart? No need to choose**

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Binary black holes emit gravitational waves (GWs) as they inspiral towards coalescence. In this study, we investigate the impact of such GWs onto the circumbinary disk around stellar-mass black holes, using general relativistic hydrodynamical simulations coupled with a general relativistic ray-tracing code. We show that, due to the proximity to the binary, pre-merger GWs leave an imprint onto the disk, leading to quasi-periodic patterns in the X-ray lightcurve.

**Proof-of-principle mass measurement of the black hole X-ray binary H1743-332**

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Modern reflection modelling is known to be able to constrain both the ionisation and the electron density of the accretion disc around the black hole (BH) in an X-ray binary (XRB). However, these properties can also be used to calculate the X-ray flux incident onto the disc from an illuminating corona. By comparing the observed flux of the corona and of the reflected X-ray emission, the ratio of the BHs mass and the distance to the BH can be constrained. I will present work simultaneously analysing XMM-Newton and NuSTAR observations spanning the 2014, 2016, and 2018 outbursts of BH XRB H1743-332 using this method. While this source is known to lie within the galactic centre, its high extinction has prevented the use of traditional methods to estimate the BH mass. Thus this proof-of-principle work points towards an interesting mass of 14 $M_\odot$, and demonstrates a method by which we can probe the properties of systems which so far remain elusive. This will have important implications of our understanding of the galactic XRB populations BH mass function.

**The current state of Galactic Black Holes Winds observations through X-ray absorption lines**

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The first detection of X-ray wind signatures (mainly FeXXV/XXVI absorption lines between 6 and 8keV) in Black Hole Low Mass X-ray Binaries (BHLMXBs) took place more than 20 years ago. In the last decade, it has become apparent that these winds are only detected in strongly inclined objects, hinting at them originating from the disk, although there is still no unequivocal evidence for an MHD or Thermal origin. On the other hand, most detection occur during the soft spectral state (see e.g. Ponti et al. 2012), for reasons yet to be understood.

We present an update of the current state of wind detection in BHLMXBs, through the analysis of all available XMM-EPIC data of all LMXBs currently classified as BH/BH candidates, from the BlackCAT (Corral-Santana et al. 2016) and WATCHDOG (Tetarenko et al. 2015) catalogs. We will discuss the number of sources with statistically significant detection in the 6.-8. keV band, the associated EWs and blueshifts, and the consequences on the inclination/spectral state dichotomy.

**Dual Comptonization model for the type-B QPOs in GX 339−4**

Valentina Peirano[1], Mariano Méndez[1]
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Understanding the energy-dependent rms and lags of quasi-periodic oscillations (QPOs) can help elucidate the properties of the accretion flow in black-hole (BH) X-ray binaries and the, still enigmatic, mechanism that produces those QPOs. In this talk, I will present results using the time-dependent Comptonisation model developed by Karpouzas et al. (2020) to fit the energy-dependent fractional rms amplitude and lags of the type-B QPO of GX 339−4. We find that, as in the case of the type-B QPO in another BH system, MAXI J1348−630, the lags increase both at low and high energies, with the minimum of the lags at $\sim$3 keV. We fit simultaneously the time-averaged spectrum of the full observation and the rms and lag spectra of the QPO, and find that the rms and lags of the QPO are due to Comptonisation in two different regions in the system. I will discuss the inferred geometrical and physical properties of these Comptonising regions, the nature of their interaction with the accretion disc and, in the context of similar studies on other BH systems, the potential origin of the type-B QPOs we observe.

**An XMM-Newton view of extreme accretion and ejection in ultraluminous X-ray sources**

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Ultraluminous X-ray sources (ULXs) are the brightest X-ray binaries. They are mainly powered by stellar-mass black holes and neutron stars accreting above their Eddington limit. This was understood after the discovery of coherent pulsations and cyclotron lines in some ULXs, indicating that at least a fraction of them hosts neutron stars as compact objects and, finally, the discovery of powerful winds that were predicted by theoretical models of super-Eddington accreting compact objects. The latter was only possible thanks to high-resolution X-ray spectrometers aboard XMM-Newton. ULX winds carry a huge amount of power owing to their relativistic speeds (0.1-0.3c) and are able to significantly affect the surrounding medium, likely producing the observed 100s pc superbubbles, and limit the amount of matter that can reach the central accretor. The study of ULX winds is therefore quintessential to understand 1) how much and how fast can matter be accreted by compact objects and 2) how strong is their feedback onto the surrounding medium in the regime of high accretion rate such as for quasars and supermassive black holes at their peak of growth. I will provide an overview on this phenomenology and highlight exciting results from some recent spectroscopic campaigns.

## Multi-wavelength spectral analysis of O star + black hole binaries

Varsha Ramachandran[1], Lida Oskinova[2], Wolf-Rainer Hamann[2], Andreas Sander[1]
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To understand the complex behavior of HMXBs with black hole companions, detailed knowledge of the massive donor wind is essential. However, only a few such systems are known so far. Our current understanding of HMXBs with black holes is primarily based on Cygnus X-1 in our Galaxy. Yet, this prototypical system has not been analyzed with the current generation of stellar atmosphere codes. In this talk, I will present a detailed re-analysis of Cygnus X-1 and a new analysis of the extragalactic HMXB M33 X-7 using simultaneous XMM and HST observations. M33 X-7 is the only known eclipsing black hole binary with a very massive O-star and black holes known in HMXB systems. We performed a detailed spectroscopic analysis (Xray+UV+optical) at different orbital phases providing stellar and wind parameters of the metal-poor donor. I will discuss the detailed wind structure of the donor, wind accretion, and the impact of X-ray photoionization. Our new analysis suggests much lower masses for M33 X-7 and the donor is nearly filling its Roche lobe. The accretion luminosity derived using the Bondi-Hoyle calculation was found to be lower than the observed X-ray luminosity, possibly due to the deceleration of the wind by strong X-ray ionization.

## Unveiling the disc structure in the pulsing ultraluminous X-ray source NGC 1313 X-2 with XMM-Newton

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Super Eddington accretion is one of the most interesting and extreme processes in the life of black holes and neutron stars, with a significant impact onto their evolution. Ultraluminous X-ray sources (ULXs) are nearby accreting binaries with luminosities above the Eddington limit of a stellar-mass black hole ($\sim 10^{39}$ erg/s), and represent the ideal systems in which we can investigate super-Eddington accretion regime. In this talk, I will present our recent results (Robba et al. 2021) on the spectral analysis of NGC 1313 X-2, whose baseline model consists of two thermal blackbody components with different temperatures plus an exponentially cutoff powerlaw. We discovered that the correlation between luminosity and temperature for cool component is consistent with a wind- dominated X-ray emission region. Instead, the (L, T) relationship for the hottest component argues in favour of super-Eddington accretion with a thicker disc.

Secondly, I will compare these results with those obtained for the BH-ULX candidates, i.e. NGC 55 ULX-1 (in prepration) and NGC 55 ULX-2 (submitted).

### Uncovering the peculiarities of the ULX NGC 7793 P9

Alba Rodríguez Castellano[1], Felix Fürst[2], Peter Kretschmar[3], Luis Abalo Rodríguez[1], Marianne Heida[4], Dominic Walton[5]

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NGC 7793 P9 is a little-known ultra-luminous X-ray source (ULX) 3.40 Mpc away that has shown very intriguing behaviour. Hu et al. (2018) proposed that it is possibly a black hole X-ray binary due to its state change which could be connected to a change from sub- to super-Eddington accretion rate. Here we present a detailed spectral analysis of archival and new XMM-Newton and NuSTAR data, describing them with a two-component accretion disk model. While most data follow a canonical $L \propto T^4$ relation, one observation is a stark outlier, with a much higher inner disk temperature than expected. This might indicate a significant change in accretion geometry as a function of flux. Additionally, we find that all observations, below and above the fiducial Eddington-limit of $10^{39}$ erg s$^{-1}$ can be described with the same two-component disk model and no further state changes are evident in our data. Moreover, we do not discard the possibility that NGC 7793 P9 may actually be a pulsar ULX. Thus, we support a scenario in which the use of a two-component disk model can explain all NGC 7793 P9's states and where an accretion geometry change by cause of flux's variability could be present.

### On the infrared coincidence: what is the jet contribution to the X-ray power law in GX 339-4?

David Russell[1]

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The hard X-ray power law - prominent in the hard spectral state in black hole X-ray binaries - is generally agreed to be due to thermal Comptonization in the inner accretion flow. Optically thin synchrotron emission from compact jets is commonly seen at infrared wavelengths in the hard state. The extent of this synchrotron spectrum to higher energies remains uncertain. However in some systems, there is evidence for two X-ray power laws with similar slopes. It has been proposed that optically thin synchrotron emission from compact jets could produce the second, fainter power law. Here, a multi-wavelength study of GX 339-4 is presented. We find that when the jet dominates the IR emission, the X-ray power law and the IR–to–X-ray power law spectral indices are consistent with each other, implying that the X-ray spectrum, extrapolated to IR wavelengths, agrees with the observed jet flux. This suggests they could be the same power law with the same origin, or that this is a coincidence. The X-ray power law never appears to be fainter than the jet power law extrapolated from IR to X-ray, implying that the jet contribution imposes a lower limit to the X-ray flux.

**The role of strongly magnetized disks in the spectral hysteresis of X-ray binaries**

Nicolas Scepi[1]
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Since the finding that the magneto-rotational instability can drive turbulence, the role of magnetic fields in standard accretion disk models has been confined to producing an effective turbulent viscosity. However, in the past ten years simulations have shown that the properties of strongly magnetized disks largely deviate from standard models. The magnetic field can launch powerful outflows, produce accretion through vertically elevated layers or non-axisymmetric structures and accelerate particles to very high energies. All of these effects dramatically affect the observational signature of accretion disks. In this talk, I will show a comprehensive analysis of a set of global GRMHD simulations showing how the properties of strongly magnetized accretion disks vary when going from thick, hot disks to cold, thin disks. I will show in particular that in thin, luminous disks the magnetic field is able to maintain the vertical density structure to larger heights than the thermal scale height and drive accretion at much faster inflow speed than the standard theory would predict. I will show how the impact of the magnetic field on the density structure will affect the thermal and radiative evolution of luminous accretion disks and how it could drive a natural hysteresis in X-ray binaries.

**Tracking State Transitions in Low-Mass X-Ray Binaries Using a Temporal Scale**

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It is now widely accepted that black hole (BH) low-mass X-ray binaries (LMXBs) recurrently follow a similar evolution when they undergo outbursts, displaying various spectral states likely connected to different accretion regimes on to the BH. Similar to BH transients, LMXBs, hosting a neutron star (NS), are also known to undergo occasional outbursts where they too exhibit spectral patterns and transitions reminiscent of several states. In this work, the results of a temporal analysis of observations for a sample of nine LMXBs are presented. We use archival RXTE data to extract a characteristic timescale and construct an intensity-variability diagram (IVD) and demonstrate its utility in tracking the spectral changes in a sample of well-studied BH and NS (Atoll and Z-type) binaries.

**Long-term spectral evolution of Cyg X-1 as seen by INTEGRAL**

Philipp Thalhammer[1], Joern Wilms[1], Jerome Rodriguez[2], Philippe Laurent[3], Floriane Cangemi[2], Victoria Grinberg[4], Tobias Beuchert[5], Thomas Siegert[6], Ingo Kreykenbohm[1], Celia Sánchez-Fernández[7], Katja Pottschmidt[8]
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We present an overview of the long-term spectral evolution of Cyg X-1 over the last 19 years as seen by INTEGRAL. We analyzed the available IBIS/JEM-X & SPI data spanning 10-2000 keV. We identified state transitions and modeled the spectrum in low-hard, high-soft and intermediate state corresponding to different accretion disk configurations. This analysis includes an additional 2.2 Ms of exposure since the last comparable analysis has been performed, most of which in the low-hard state, allowing us to significantly improve on statistical uncertainties. Further, we show the evolution of spectral parameters through the years tracing changes in the source geometry.

**Quasi periodic eruptions from an intermediate mass black hole in an extra-galactic globular cluster?**

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We have recently identified a possibly regular flaring behavior in the ultraluminous X-ray source XMMU J122939.7+075333, located in the globular cluster RZ 2109 in the Virgo galaxy NGC 4472 (Tiengo et al. 2022, A&A in press, arXiv:2202.08478). Its peculiar properties in the X-ray and optical band can be explained by the repeated partial tidal disruption of a white dwarf in a highly eccentric orbit around a 1000 Msun black hole (BH). A similar scenario, involving BHs with three orders of magnitude larger masses, has been proposed to interpret the quasi-periodic eruptions (QPEs) that were recently detected in the nuclear regions of galaxies. If the regular flaring pattern of XMMU J122939.7+075333 were confirmed by future observations, it would be a scaled-down example of the QPE phenomenon in a different environment, but characterized by a similarly high stellar density, which makes the formation of such eccentric systems possible.

### The rejection of the requirement of magnetic winds

Ryota Tomaru[1], Chris Done[1], Junjie Mao[2]
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Blackhole binary systems show accretion disc winds, seen via blue-shifted, highly ionised Fe XXV and XXVI (He and H-like) absorption lines in their spectra. The driving mechanisms of these winds are still under debate, whether they are magnetic and link to the jet or thermal and link to X-ray heating of the disc. A single observation of an unusual low ionisation wind in GRO J1655-40 makes the strongest case for magnetic driving, as the spectrum includes metastable lines from Fe XXII (B-like), which are density sensitive. These allow the launch radius to be determined, which is far too small for thermal driving. However, this density was derived from assuming the metastable level was populated only by collisions. Instead, we include radiative cascades down from upper excited levels and find the density is reduced by more than an order of magnitude, bringing it into line with thermal wind models. We show a specific radiative-hydrodynamic simulation of a thermal-radiative wind which gives good overall agreement with the observed spectrum. Our result removes the requirement for magnetic driving in these data by showing that they can be explained by a thermal (or thermal-radiative) wind.

### IR quasi periodic oscillations from black hole X-ray binaries

Federico Vincentelli[1]
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Throughout their outburst, black hole X-ray binaries (BHXBs) are known to show strong stochastic X-ray variability, including quasi-periodic oscillations (QPOs). Such oscillations revealed to be one of the most powerful tools to constrain the geometry of the accretion flow around compact objects. Despite this, many aspects of these features are still unclear. Recent sub-second optical-infrared (O-IR) observations of these sources have led to the discovery ofquasi periodic oscillations also in these bands. This opened the possibility to study the jet andthe external regions of the hot inflow with these powerful features. Here we present the characterization of the quasi periodic oscillations from three black hole transients: GX 339-4, MAXIJ1535-571 and MAXI J1348-630. The QPOs measured in these three objects show significantly different properties, which can therefore be used to constrain the physical parameters of these systems. In particular, we discuss physical implications of the the relative amplitude between the X-ray and the IR QPO and their lags for the state of the art models regarding jet and hot inflow.

**Theory Meets Reality: Testing Accretion Disk Models with LMC X-3 and GRO J1655-40**

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We will present a detailed investigation of X-ray spectral models used to fit the thermal accretion disk emission in black-hole X-ray binaries. We fit 2000 RXTE observations of GRO J1655-40 and LMC X-3 to explore the nature of the accretion disk in strong gravitational fields via non-relativistic and relativistic disk models. We find that the non-relativistic multi-color disk blackbody model (diskbb) gives significantly (about 50-60%) higher values for disk temperatures and lower (often unphysical) inner disk radii than relativistic disk models. Our study clearly shows the importance of self-consistent modeling of the thermal emission in accreting compact objects, especially when estimating the black hole spin with the continuum-fitting method. We will discuss the implications of our findings on interpretation of previous results with RXTE observations as well as our planned extension to a wider population of accreting black holes and application to more sensitive X-ray data (XMM-Newton, NICER, Chandra).

**Accretion flow, pair production and jet in the black-hole X-ray binary MAXI J1820+070**

Andrzej Zdziarski[1]
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I will discuss our results on the hard spectral state of accreting black-hole binary MAXI J1820+070 (Zdziarski et al., 2021a, b, ApJL, 2022a, b, ApJ). We analyse X-ray spectra from NuSTAR and Insight-HXMT and find the accretion disc is truncated at more than 10 gravitational radii. The X-rays and soft gamma rays are emitted by a two-component hot accretion flow surrounding the disc via Comptonization. These spectral results are supported by timing analyses of De Marco et al. 2021 and Dzielak et al. 2021. Thanks to simultaneous spectra from INTEGRAL, we find the electron distribution is hybrid, i.e, predominantly thermal but with a significant non-thermal tail. The spectra are measured up to about 2 MeV, which allows us to accurately measure the electron-positron pair production rate. We find the pair abundance within the hot flow is low, which is supported by the lack of a measurable annihilation feature. However, the gamma rays also produce pairs in the magnetically-dominated base of the jet, which, as follows from the contemporaneous radio-to-optical data, can then provide most of the synchrotron-emitting electrons upstream in the jet. Finally, by comparing the jet and accretion emission we find the hot flow can be magnetically arrested.

## The evolution of the corona in MAXI J1535571 through type-C quasi-periodic oscillations with Insight-HXMT

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Type-C quasi-periodic oscillations (QPOs) in black hole X-ray transients can appear when the source is in the low-hard and hard-intermediate states. The spectral-timing evolution of the type-C QPO in MAXI J1535571 has been recently studied with Insight-HXMT. Here we fit simultaneously the time-averaged energy spectrum, using a relativistic reflection model, and the fractional rms and phase-lag spectra of the type-C QPOs, using a recently developed time-dependent Comptonization model when the source was in the intermediate state. We show, for the first time, that the time-dependent Comptonization model can successfully explain the X-ray data up to 100 keV. We find that in the hard-intermediate state the frequency of the type-C QPO decreases from 2.6 Hz to 2.1 Hz, then increases to 3.3 Hz, and finally increases to 9 Hz. Simultaneously with this, the evolution of corona size and the feedback fraction (the fraction of photons up-scattered in the corona that return to the disc) indicates the change of the morphology of the corona. Comparing with contemporaneous radio observations, this evolution suggests a connection between the corona and the jet when the system is in the hard-intermediate state and about to transit into the soft-intermediate state.

# Chapter 4

# Cosmology, surveys, dual AGNs

**Quasars as high-redshift standard candles**

Guido Risaliti[1]
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I present the latest results on the calibration and analysis of the non-linear UV to X-ray luminosity relation in quasars, based on a sample of several thousand sources with available spectra in both the X-ray and the optical/UV bands. I will show that 1) the observed dispersion of the relation for the highest quality observations is as small as 0.09 dex; 2) this residual dispersion can be fully explained in terms of variability and disk inclination, implying a universal relation between the accretion disk emission and the X-ray corona over more than 5 decades in luminosity, and over the whole z=0-7 redshift range; 3) the Hubble diagram of quasars derived from this study shows a ¿5 sigma tension with the Labda-CDM model.

# Name Index