Feeding the spinning top - Accretion-induced torques onto young and strongly magnetized neutron stars in high-mass X-ray binaries

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Book of Abstracts

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Spectral and timing signatures in (Be) High-Mass x-ray binaries

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The basic picture of what forms the pulsed X-ray emission in strongly magnetized accreting pulsars is understood since decades, but the wealth of current data greatly exceeds our ability to model them.

HMXB are variable on many timescales, from spin, to orbit, arriving to super-orbital modulations. Variability on time scales above the spin period is instrumental to explore the accretion environment and constrain properties of the binary environment, such as clumpiness of the wind and large-scale structures as accretion wakes, but it might also allow us to disentangle emission from the different magnetic poles.

To investigate the geometry of the accretion stream and the optical properties of matter in a strong magnetic field, we need to fold the light curves at the spin period to accumulate energy-dependent pulse profiles. Their modeling is particularly challenging, owing to pronounced asymmetries, and sharp features emerging just at some energies. They suggest that the thin accretion column forming in strong magnetic fields might be amplified by gravitational lensing at some phases or self-obscured at others. However, there is not an established way of disentangling single-column contributions.

Each source shows different phenomenology and requires dedicated study, while general patterns have not been clearly highlighted, despite the deepness of archive mining. Modeling is very challenging, due to the difficulty of coupling matter and radiation in the vicinity of a neutron star. A push forward might come by federating intellectual resources for modeling and exploiting new missions with higher collecting area to explore shorter time scales.

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The peculiar pulsed fraction spectra of V0332+53: hints for complex cyclotron line shape

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Pulse profiles of X-ray pulsars are invaluable tools for understanding emission mechanisms, system geometry, and radiation transfer under extreme conditions. By extracting energy-dependent pulse profiles Ferrigno (2023) showed how the changes in the pulse shape at energies corresponding to the cyclotron resonance scattering features, provide a quantitative way of determining the feature main properties (e.g. position and spectral width) with the same relative uncertainty given by the usual tools of spectral analysis. In this contribution, I will show how the application of the same method to the accreting source V0332+53 yields surprising results regarding the shape of its broad cyclotron feature. We studied the pulsed fraction spectra for all the available NuSTAR observations, thus sampling source luminosities different by a factor more than 30. We found some common key characteristics:a two-hump continuum with a local minimum around 10 keV and a double-peaked feature at the fundamental cyclotron energy, and a clear lag discontinuity at the same energies. The interpretation of the features at the fundamental cyclotron line energy has lead us to new clues

for the spectral modelling of the cyclotron line in the energy spectra in a self-consistent picture, revealing the presence of cyclotron emission wings at both sides of the cyclotron line energy.

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A detailed spectral-timing NUSTAR view of the HMXB 4U 1901+03

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The spectral emission of accreting X-ray pulsars is complex due to their non-isotropic nature and the inclination of the line of sight with respect to the geometry of the system, which influences the observed phase variability at the spin frequency. Recently, Ferrigno et al. (2023) introduced a method to compute pulsed profiles with the energy resolution of the NuSTAR satellite, enabling detailed analysis of the Pulsed Fraction (PF) across different energy bands. This approach revealed Gaussian-like features in the PF, corresponding to well-known spectral signatures, such as the iron fluorescence line and cyclotron resonance scattering features (CRSFs), superimposed on an increasing trend of PF values with energy.
I applied the Ferrigno et al. method to four NuSTAR observations of the HMXB 4U 1901+03 during its 2019 Type II outburst. By analyzing the energy- and phase-resolved PF spectra, I explored the evolution of the pulsed fraction and harmonic content with the source's luminosity state. Observations near the outburst peak exhibit similar spectral properties, as do those taken during the descending phase, where the luminosity is significantly lower. The synergy between PF spectrum analysis, harmonic content, and phase-resolved spectra sheds light on the variability of the CRSF and its correlation with luminosity and phase.

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The extremely variable cyclotron line of 4U 1538-522 and its connection with the energy dependent pulse profiles

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We present a comprehensive study of the accreting X-ray pulsar 4U 1538−522 using timing analysis as a diagnostic tool for spectral features. Our pipeline developed for the NuSTAR mission, enables the creation of pulsed fraction (PF) spectra with an energy resolution adapted to that of the instrument. By constructing the PF spectrum of 4U 1538 this way, a broad bump can be observed less than 1 keV below the spectral value of the cyclotron line. In the phase-resolved spectroscopy, we observe extreme variability of the line, which correlates with the shape of the pulse profile. We retain this variability due to a geometric effect: assuming the emission mode is both via the pencil and fan modes, the angle between our line-of-sight and the neutron star's magnetic field might vary in a way to encompass both the zero and 90 degrees value, so that we sample the extreme values of the

cross-section for the cyclotron resonant features. We also discuss our findings in the context of other sources which show a different behavior. Our approach of using timing analysis as a complementary part of the spectral analysis, not only improves our understanding of the accretion geometry in 4U 1538−52 but also sets the stage for future research.

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Emission from accreting strongly magnetised neutron starts: evidence forged by anisotropy

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Strongly magnetised neutron stars in X-ray binaries exhibit a wide variety of energy- and phase-dependent observational properties. Taken together, these observables can provide crucial insights into the physical conditions and radiative processes within the accretion channel near the neutron star surface. However, their diversity presents substantial challenges for physical interpretation, owing to the complex nature of spectral formation in a strongly magnetised accretion flow. It involves processes such as redistribution through resonant Compton scattering off relativistic electrons, the coupling of magnetised plasma and vacuum effects on the propagation of polarised radiation, and the extended geometry of the emission region. These effects, caused by a magnetic field of the neutron star, induce a strong anisotropy into the problem, which is further enhanced by gravitational lensing. As a result, we have not only the phase variability of spectral properties but also significant systematic uncertainties when attempting to infer physical characteristics from the observables under the assumption of isotropic emission. This is particularly true for efforts to determine the mass-accretion rate from the observed flux and to estimate the strength of the surface magnetic field from cyclotron lines in the X-ray spectra. In this talk, I will provide an overview of the relevant radiative processes, polarisation effects, and geometric factors shaping the emission from an accreting, strongly magnetised neutron star, and discuss ways to disentangle these effects using physical modelling, with a focus on anisotropy.

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First look with XRISM into Stellar Wind Accretion in High-Mass X-ray Binaries

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The spectral and timing behaviour of neutron star high-mass X-ray binaries (HMXBs) offers a unique opportunity to investigate accretion onto compact objects and the wind structures of massive stars. In particular, understanding X-ray emission from neutron stars is a critical topic of research for current and future astrophysical studies, as highlighted by its prominence in the science cases of the upcoming NewAthena mission. In our study, we focus on an observation of the key source Vela X-1, which was obtained during the first cycle of the Guest Observer programme of XRISM. We also present results obtained simultaneously with XMM-Newton and NuSTAR. This exceptional dataset enables high-resolution broadband spectroscopy of Vela X-1, covering the energy range from 0.5 to 79 keV. XRISM/Resolve reveals for the first time the doublet of the emission lines of FeKα_1 and FeKα_2 as well as NiKα_1 and NiKα_2. Additionally, we investigate the clumpy structure of the material being accreted by the neutron star and provide valuable data for cross-calibration studies among three of the most modern and widely used X-ray telescopes.

2b / **23**

The delicate interplay between accretion, ejection and magnetism in neutron stars X-ray binaries

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Matter ejection, in the form of either winds or jets, is ubiquitous in accreting X-ray binaries. Although it is clear that accretion and ejection are profoundly intertwined in these types of systems, the origin and the details of such an interconnection are yet to be unraveled. This is particularly true for systems where a low-magnetized neutron star (NS) accretes matter from a low-mass companion star (NS low-mass X-ray binaries, LMXBs). Indeed, unlike the case of accreting black holes, in NS LMXBs the already delicate interplay between accretion and ejection may be further complicated by the presence of, e.g., the NS magnetic field, the boundary layer and the emission from the NS surface. For instance, jets in NS LMXBs have been claimed to be more collimated than in BH LMXBs and their occurrence sometimes seems to be unrelated to the spectral state. X-ray winds, on the other hand, have been often detected in states where they were not expected, in particular in a class of NS LMXBs, the Accreting Millisecond X-ray Pulsars (AMXPs), where the channeling of the accretion flow along the magnetic field lines makes these systems visible as rapidly spinning X-ray pulsars. Finally, AMXPs typically drive more powerful jets than other (non-pulsating) NS LMXBs and their rapid orbital expansion can be explained by strong mass outflows. In this talk, I will review the emerging pattern of peculiar outflows in NS LMXBs, the possible implications for other types of sources such as NS high mass X-ray binaries and the key role that future multi-band observing campaigns will play in clarifying its physical origin.

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X-ray mode switching in transitional millisecond pulsars: insights from GRMHD simulations and ray-tracing

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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 this so-called "X-ray mode switching" behavior 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 specific accretion regime or "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. One still needs to explain the causality link, the emission process involved and the energy source, all sources of debate (see e.g. Campana+16, Veledina+19).

We will present dedicated 2D/3D GRMHD simulations of an accreting MSP that we post-process with a GR ray-tracing code, including thermal synchrotron emission, absorption and scattering, to produce synthetic spectra. This way, we are able to draw a causality connection between the flow location (with respect to the light cylinder) and the high/low X-ray emission, to identify the key components driving these switches, and distinguish between the different scenarii proposed in the literature. Beyond the X-rays, we show how this model fits the multi-wavelength constraints and gives predictions for the gamma-ray flux in the low state.

3a / **4**

Collimation of outflows in moderately magnetized neutron stars

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We perform general relativistic radiative magnetohydrodynamics simulations
(GRRMHD) of super-Eddington disk accretion onto moderately magnetized neutron stars with surface magnetic field of $10^{10} - 10^{11}$ Gauss. The apparent luminosity of the object shows, surprisingly, to be larger for the weaker magnetic field. The widening of the collimation cone with increase in the field strength brings the decrease in apparent luminosity.

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Radiative efficiency in the radiative GRMHD simulations of super-Eddington accreting neutron stars

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We study the energy flow and radiative efficiency in numerical simulations of super-Eddington accreting magnetized neutron stars. A total of 10 numerical simulations were conducted using the

radiative GRMHD code KORAL. The strength of the magnetic dipole ranged from 10 to 100 GigaGauss and the accretion rates varied between 100 and 1000 Eddington luminosity (L_{Edd}/c^2). It is found that overall efficiency decreases with increasing the strength of the magnetic dipole of the neutron star. The simulation with a strong magnetic dipole (100 GigaGauss) shows lower radiative efficiency than the simulation with a weak magnetic dipole (10 GigaGauss). It is also shown that a higher accretion rate results in greater energy being released as kinetic energy in outflows compared to a lower accretion rate simulation. This leads to reduced radiative efficiency in the high accretion rate simulation. However, the powerful outflows produced in the high accretion rate simulation (1000 L_{Edd}/c^2) cause beaming effects, which leads to a highly super-Eddington apparent luminosity. Our study concludes that neutron stars with a magnetic dipole in order of 10 GigaGauss and accretion rates exceeding 300 Eddington luminosity can act as ultraluminous X-ray sources.

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Numerical Simulations of Accreting Neutron Stars in a General Relativistic Framework

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Numerical modelling of accreting neutron stars is crucial for unravelling the physical origins of the diverse observational signatures detected from these systems. However, global simulations of these sources have remained a challenging computational problem as they require accurate modelling of the complex interplay between gravity, magnetic fields, surface emissions, and the accretion flow. The neutron star surface magnetic field plays a vital role in determining the nature of accretion flow at the inner regions of the star, and understanding the star-disk magnetic field interactions in these regions is key to understanding various astrophysical processes like angular momentum transport, jet formation, and disk winds. Additionally, the surface X-ray emission from accreting pulsars originating from accretion hotspots formed as a result of the magnetically channelled accretion flow hitting the stellar surface is significantly affected by the inner accretion dynamics. Understanding the accretion dynamics requires full-scale GRMHD simulations of the magnetized accretion disks. In this talk, I will present results from a suite of 2D and 3D global GRMHD simulations of accreting neutron stars with dipole, quadrupole, and quadrudipolar stellar field geometries and discuss accretion dynamics, outflows, and pulse properties observed in these simulations. We observe outflows in the simulations in the form of highly collimated jets, which are produced due to the anchored magnetic field of the rotating star in analogy with the Blandford-Znajek process. In the case of accreting stars, magnetic field interactions are observed to play a critical role in determining the jet power. We also characterize the pulse properties resulting from the accretion hotspots and find that the pulse amplitudes typically range between 1 - 12% rms, which is consistent with the values observed in accreting millisecond pulsars.

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Spin frequency zoology –the diversity of accreting X-ray pulsars

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The spin frequency histories over many years as traced by the Fermi Gamma-Ray Burst Monitor (GBM) show a wide variety of behaviours, ranging from clear trends of spin-up or spin-down to apparently random changes.
We will present first results of a systematic effort to characterize the spin frequency histories of all accreting X-ray pulsars for which Fermi GBM data exists, undertaken as a MSc thesis work at Universidad Complutense Madrid. This will be work in progress for discussion and feedback in order to fine tune the creation of the planned catalogue of results.

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Accretion-induced Torques onto Highly Magnetized and Young NSs in X-ray Binaries

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Accreting objects in binary systems have a crucial impact on the evolution of the system as a whole. If the accreting object possesses a strong magnetic field, the rotating magnetic field drives the evolution of the surrounding and embedding plasma. At the same time, the spin evolution of magnetized accretors is directly related to the magnetic field strength. This puts models for the accretion process in an interesting position: On the one hand their knowledge is necessary to model the long-term evolution of binary systems harboring strongly magnetized NS. On the other hand, with those models it is possible to extract key parameters of binary systems: The magnetic field of the accretor, the distance of the
system and its orbital parameters. In this talk I will discuss general assumptions of torque models and showcase the application of suggested models to a sample of HMXB systems.

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Compiling our knowledge of astronomical objects on the example of BeXRB outbursts

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Common data archives do not allow scientifically motivated queries, like “find observations with a time resolution better than … at which the absorption column density towards the source was higher than …” or “find accreting neutron stars associated with the Large Magellanic cloud with a spin-period in the range of …”. We will present a database concept which can answer this kind of queries. Thus, time-consuming archive investigations including the reduction and quick analyses of tons of data will be a relict of the past. On the example of Be X-ray binaries (BeXRBs), we will present a study of their long-term monitoring data. The resulting comprehensive catalogue and properties of BeXRB outbursts will be ingested into our database. This enables us to look for correlations between outburst properties and further BeXRB properties like their orbital or stellar parameters.

4a / **9**

Slowly spinning neutron stars in high-mass X-ray binaries

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High mass X-ray binaries (HMXBs) with OB type supergiant companions mostly host slowly spinning neutron stars. The slowest pulsar in a HMXB, to date, is AX J1910.7+091, showing pulsation with a periodicity of P = 36200+/-110 s and a pulsed fraction of about 60%. This very long neutron star spin period has been suggested to be explained within a quasi-spherical settling accretion model, applicable to low luminosity, wind-fed, X-ray pulsars. Among HMXBs with supergiant companions, there is a sub-class of sources with transient X-ray activity, the so-called Supergiant Fast X-ray Transients (SFXTs). About a half of them host slow pulsars as well (with spin periods from 21 s to 1240 s), while in the other half pulsations are not observed, maybe indicative of very long period pulsars, still awaiting detection. The quasi-spherical settling accretion model can be applied to SFXTs, as well. In this framework, an equilibrium pulsar period cab be reached rapidly, and its value depends not only on the neutron star magnetic field, but also on the supergiant wind velocity. This latter quantity, although usually assumed to be 1000 km/s, is one of the big unknowns in wind-fed HMXBs, together with the mass loss rate from the supergiant. These two quantities, characterizing the properties of the supergiant wind, are crucial to understand also the X-ray behaviour of HMXBs, and to possibly uncover the physical reason why SFXTs behave so differently from persistent wind-fed HMXBs. Our recent detection from the first time of a neutron star HMXB (a SFXT) at mm-wavelengths is an important step towards the understanding of this dichotomy, and also in the determination of the equilibrium spin periods in these pulsars.

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Accretion onto the Slowly Rotating Magnetar Candidate 4U 0114+65

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4U 0114+65 is a unique high-mass X-ray binary (HMXRB) system, featuring the luminous B1Ia supergiant V* V662 Cas and one of the slowest rotating neutron stars ever known, with a spin period of approximately 2.6 hours. This exceptionally slow spin period suggests that the neutron star may have been born as a magnetar. Additionally, the system exhibits secular spin-down with occasional periods of reversal.

A remarkable characteristic of 4U 0114+65 is the variability of its individual X-ray pulses, with no two pulses appearing alike. Some observations reveal a cyclical decrease in count rate within individual pulses, observable in both high- and low-energy light curves. The slow pulsation cadence of the neutron star provides a unique opportunity to study intricate details of the accretion process. Notably, the light curves exhibit spikes consistent with Rayleigh-Taylor instabilities near the magnetosphere.

We propose that fluctuations in the efficiency of Compton cooling drive this variability throughout an accumulation cycle. The source gradually accumulates matter until the density surpasses a critical threshold, triggering a transition to a more efficient Compton cooling regime. This leads to a higher mass accretion rate and, consequently, increased brightness.

4a / **13**

Pulse period evolution in ULX Pulsars

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I will give a brief overview over the history of pulse period evolution in the small class of ultra-luminous X-ray pulsars (ULXPs). ULXPs are super-Eddington neutron stars, with sustained luminositities above 10e39 erg/s. I will focus on three sources, NGC 779 P13, NGC 5907 ULX-1, and NGC 300 ULX-1, which all show different behavior. All of them are likely powered through direct accretion from a massive star, and have shown long-term "off-states" during which they were no longer detected. However, while NGC 5907 ULX-1 clearly spun-down during the off-state, indicating that accretion had ceased, NGC 7793 P13 and NGC 300 ULX-1 continued to spin-up almost unabated. Our interpretation is that in this case the off-state was caused by obscuration and not by a drop in accretion rate. This behavior highlights that observed flux and accreted materials do not have to be correlated, and that inferring physical properties like magnetic field from spin-up and luminosity is not straightforward.

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Refining Torque Models in X-ray Pulsars: Insights from Super-Eddington BeXRBs

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X-ray pulsars, predominantly found in Be X-ray binaries (BeXRBs), are powered by accretion processes. The study of giant outbursts in BeXRBs has gained renewed importance following the discovery of pulsating ultra-luminous X-ray sources (PULXs), which demonstrate the feasibility of stable accretion onto neutron stars (NSs) at super-Eddington rates. Estimating the magnetic field strength in PULXs often relies on standard torque models, but recent theoretical advancements suggest these models must account for changes in accretion disk structure under super-Eddington conditions. Motivated by these developments, we analyzed torque models during super-Eddington outbursts of BeXRBs monitored by Fermi/GBM. Using a Bayesian framework, we fit accretion models and binary orbital parameters, exploring degeneracies between key factors such as inner disk radius, source distance, and magnetic field strength. This methodology was applied to selected systems, with notable results for Swift J0243.6+6124, where super-Eddington transitions were identified, and RX J0520.5-6932, which exhibited discrepancies between optical and X-ray periodicities. Our findings highlight the need for refined models to better understand the complex interplay of physical processes in these extreme systems.

4b / **6**

Pulsating ultraluminous X-ray sources: probing the high-energy tail of high-mass X-ray binaries

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Ultraluminous X-ray sources (ULXs) are X-ray binaries with luminosities higher than 10^{39} erg s^{-1}. A few ULXs exhibit coherent pulsations, classifying them as pulsating ULXs (PULXs) and confirming that some of these systems are powered by highly magnetized neutron stars at super-Eddington accretion rates. Such extreme accretion rates require sustained, high-mass transfer rates, achievable only with massive companions. As a matter of fact, the few identified donor stars in PULXs are all high-mass, Be, or evolved stars (e.g. the PULX NGC 7793 P13 has a B9Ia companion), and super-Eddington outbursts have also been observed in certain Be/XBs (e.g. Swift J0243.6+6124 in our Galaxy). PULXs likely constitute the high-energy tail of X-ray pulsars in HMXBs, including those in our Galaxy and in the Magellanic clouds, while the ULX regime may represent an evolutionary phase of HMXBs, characterized by accretion via wind Roche-lobe overflow. In this contribution, I will show that PULXs display many traits of HMXBs (spin up/down episodes, propeller regime, hints of magnetic torque), making them unique sources to study the interaction between magnetic fields of young neutron stars and super-Eddington accretion flows.

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Observing Rayleigh-Taylor stable and unstable accretion through a Kalman filter analysis of X-ray pulsars in the Small Magellanic Cloud

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Global, three-dimensional, magnetohydrodynamic simulations of Rayleigh-Taylor instabilities at the disk-magnetosphere boundary of rotating, magnetized, compact stellar objects reveal that accretion occurs in three regimes: the stable regime, the chaotic unstable regime, and the ordered unstable regime. Here we track stochastic fluctuations in the pulse period P(t) and aperiodic X-ray luminosity L(t) time series of 24 accretion-powered pulsars in the Small Magellanic Cloud using an unscented Kalman filter to analyze Rossi X-ray Timing Explorer data. We measure time-resolved histories of the magnetocentrifugal fastness parameter ω(t) and we connect ω(t) with the three Rayleigh-Taylor accretion regimes. The 24 objects separate into two distinct groups, with 10 accreting in the stable regime, and 14 accreting in the ordered unstable regime. None of the 24 objects except SXP 293 visit the chaotic unstable regime for sustained intervals, although several objects visit it sporadically. The Kalman filter output also reveals a positive temporal cross-correlation between ω(t) and the independently measured pulse amplitude A(t), which agrees with simulation predictions regarding the pulse-forming behavior of magnetospheric funnel flows in the three accretion regimes.

5a / **3**

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 ~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 (with 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.

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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. 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. 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 is thought to be a product of the tidal interaction between the Large and Small Magellanic Clouds (LMC and SMC). It contains both gas and stellar components, with young stellar components (HMXBs) which are thought to have formed in situ, as well as on an 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, offering comprehensive X-ray coverage. 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 behaviour. This presentation will unveil the findings from our study of the X-ray binary population across the entire Magellanic system through the SRG/eROSITA all-sky survey. Additionally, we will showcase unique discoveries, including a Supergiant Fast X-ray transient in the LMC and an X-ray burster in the Magellanic Bridge.

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First-principles Simulations of Black-hole Accretion

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Most galaxies host a supermassive black hole (SMBH) at their center, which may power a brightcompact region, the active galactic nucleus (AGN), sometimes more luminous than the rest of the galaxy. This emission is powered by the BH rotation as well as the gravitational energy of an accretion disk of hot plasma falling into the BH. The disk produces radiation at a wide range of wavelengths, as recently imaged by the Event Horizon Telescope (EHT) and other collaborations e.g. for the SMBH M87*. In BH accretion flows, the transport of angular momentum is promoted by the magnetorotational instability (MRI), feeding on the disk's differential rotation to excite and sustain turbulence. This transfers energy from large scales to microscopic (kinetic) plasma scales, heating the accretion flow, generating large-scale magnetic fields, and accelerating particles. Accelerated electrons (but

not ions) can also emit, e.g. via synchrotron radiation. To investigate this dynamics from first principles, we present the first fully kinetic simulations of the MRI in semirelativistic electron-ion plasma characteristic of SMBH accretion disks. An important result of this work is a first-principles measure of electron and ion heating; magnetohydrodynamic simulations of accretion require these subgrid prescriptions to produce synthetic lightcurves to be compared with observations. In addition, we characterize nonthermal particle acceleration, which directly relates to observable radiation.