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Juhani Mönkkönen

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ABSTRACT

Massive stars end their lives either by collapsing directly into a black hole or by exploding as a supernova, leaving behind their collapsed core, a black hole or a neutron star (NS). NSs are a showcase of extremities: their density competes with that of the atomic nucleus and their magnetic fields are the strongest in the universe. As such, they present a unique opportunity for studying the fundamental forces of nature.

When the NS inhabits a binary system, it may accrete matter from its companion star, and accretion is a highly effective way of transforming potential energy into radiation. This means that NSs reveal themselves to us through various interactions of matter and radiation, appearing as X-ray sources to our satellites. How the X-rays vary in time and photon energy carries information of the physical processes in the NS system.

Of these processes, the interaction of accreted matter with the NS's extremely strong magnetic field is the theme of this thesis. First, matter slowly spirals in the accretion disc, until it is forced to follow the magnetic field lines in the vicinity of the NS and onto the NS's magnetic poles. Such a dramatic transformation of an accretion flow does not remain without consequences, but rather, writes itself into the details of mass density fluctuations which modulate the observed flux. Therefore, this thesis turns to timing analysis, offering a view to the different time scales of accretion: from low frequencies mapping the slow outer accretion disc to the high frequencies revealing what happens when the accretion disc encounters the magnetosphere of the NS. The standard assumptions of magnetic field structure are relaxed in light of the results.

KEYWORDS: high energy astrophysics, neutron stars, timing analysis

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TIIVISTELMÄ

Massiivinen tähti voi päättää elämänsä joko romahtaen suoraan mustaksi aukoksi tai supernovana, jolloin tähden ydin tiivistyy mustaksi aukoksi tai neutronitähdeksi. Neutronitähdet toimivat näyttämönä äärimmäisille ilmiöille: niiden tiiveys haastaa atomiydinten tiiveyden ja niiden magneettikentät ovat maailmankaikkeuden voimakkaimpia. Siten ne tarjoavatkin ainutlaatuisen mahdollisuuden luonnon perusvoimien tutkimiseen.

Kun neutronitähti sijaitsee kaksoistähtijärjestelmässä, se saattaa kerryttää ainetta kumppaniltaan, ja aineen kertyminen on hyvin tehokas tapa muuntaa aineen potentiaalienergiaa säteilyksi. Niinpä neutronitähdet näyttäytyvät röntgensatelliiteillemme moninaisten aineen ja säteilyn vuorovaikutusten kautta. Röntgenvuon ajallisen vaihtelun ja fotonien energiajakauman avulla voidaan päätellä, millaisia fysikaalisia prosesseja neutronitähtijärjestelmässä tapahtuu.

Näistä prosesseista väitöskirjan kantavaksi teemaksi valikoitui aineen vuorovaikutus neutronitähden äärimmäisen voimakkaan magneettikentän kanssa. Alkuun aine kiertyy hitaasti kertymäkiekossa kohti neutronitähteä, kunnes tämän läheisyydessä magneettikenttä kaappaa aineen kenttäviivoihinsa ja ohjaa sen neutronitähden magneettisille navoille. Tämä muutos ei jää seuraamuksitta, vaan tallentuu aineen tiheyden vaihteluun, joka myös vaikuttaa havaittuun vuohon. Tämä väitöskirja kääntyykin aikasarja-analyysin puoleen paljastaakseen laaja-alaisen näkymän aineen kertymiseen: matalat taajuudet kartoittavat kertymäkiekon hitaita ulko-osia kun taas korkeat taajuudet paljastavat, mitä tapahtuu, kun kertymäkiekko kohtaa neutronitähden magneettikentän. Tulokset kannustavat kyseenalaistamaan joitakin perusolettamuksia magneettikentän rakenteesta.

ASIASANAT: astrofysiikka, neutronitähdet, aikasarja-analyysi

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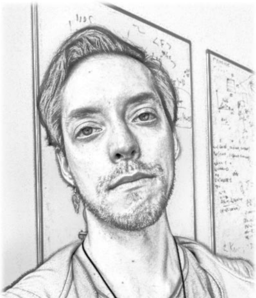

JUHANI MÖNKKÖNEN
Uppoutuu syystaivaan syvyyteen ja luonnon yksityiskohtiin, neutroneista neuroneihin. Kuvataideprojektiensa ohella hän haaveilee scifikirjailijuudesta sekä neurolingvistiikkaan perehtymisestä, koska miksipä ei.

Delves deep into the autumn sky and the details in nature, from neutrons to neurons. In addition to working on various art projects, dreams of one day writing a proper science fiction book while also trying to grasp neurolinguistics. Maybe at some point learning to choose and focus on one thing...

Table of Contents

Abbreviations

AMP	Accreting millisecond pulsar
CRSF	Cyclotron resonant scattering feature (Cyclotron line)
HMXB	High-mass X-ray binary
LMXB	Low-mass X-ray binary
NS	Neutron star
PDS	Power density spectrum
rms	Root mean square
RPD	Radiation-pressure dominated

List of Original Publications

This dissertation is based on the following original publications, which are referred to in the text by their Roman numerals:

I A. Nabizadeh, J. Mönkkönen, S. S. Tsygankov, V. Doroshenko, S. V. Molkov, J. Poutanen: NuSTAR observations of wind-fed X-ray pulsar GX 301−2 during unusual spin-up event. Astronomy & Astrophysics, 2019, 629, A101 (10 pp)

II J. Mönkkönen, V. Doroshenko, S. S. Tsygankov, A. Nabizadeh, P. Abolmasov, J. Poutanen: Discovery of a retrogradely rotating neutron star in the X-ray pulsar GX 301−2. Monthly Notices of the Royal Astronomical Society, 2020, 494, 2178-2182

III A. Nabizadeh, S. S. Tsygankov, D. I. Karasev, J. Mönkkönen, A. A. Lutovinov, D. I. Nagirner, J. Poutanen: Properties of the transient X-ray pulsar Swift J1816.7−1613 and its optical companion. Astronomy & Astrophysics, 2019, 622, A198 (8 pp)

IV J. Mönkkönen, S. S. Tsygankov, A. A. Mushtukov, V. Doroshenko, V. F. Suleimanov, J. Poutanen: Evidence for the radiation-pressure dominated accretion disk in bursting pulsar GRO J1744−28 using timing analysis. Astronomy & Astrophysics, 2019, 626, A106 (10 pp)

V J. Mönkkönen, S. S. Tsygankov, A. A. Mushtukov, V. Doroshenko, V. F. Suleimanov, J. Poutanen: Constraints on the magnetic field structure in accreting compact objects from aperiodic variability. Monthly Notices of the Royal Astronomical Society, 2022, 515, 571-580

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The following original publications coauthored by the author have not been included in the thesis.

- V. Doroshenko, V. F. Suleimanov, S. S. Tsygankov, J. Mönkkönen, L. Ji, A. Santangelo: Observations of GRO J1744−28 in quiescence with XMM-Newton. Astronomy & Astrophysics, 2020, 643, A62 (9 pp)
- A. A. Mushtukov, G. V. Lipunova, A. Ingram, S. S. Tsygankov, J. Mönkkönen, M. van der Klis: Broad-band aperiodic variability in X-ray pulsars: accretion rate fluctuations propagating under the influence of viscous diffusion. Monthly Notices of the Royal Astronomical Society, 2019, 486, 4061-4074

1 Introduction

Stars are cosmic furnaces which merge light elements into heavier ones. Ignited by the gravity of the star, this fusion of elements releases energy in their cores and makes stars shine. However, it also predicts their downfall since no fuel lasts forever. While the lifespan of a red dwarf star smaller than our Sun may be up to trillions of years, the fate of a heavier star is to burn faster and die younger. Within only a million years or so, these heavy stars will have used all of their fuel only to be left with a core of iron that no more produces energy.

Instead of a slow death, this fast lane of stellar evolution brings in an inevitable collapse either directly into a black hole for the most massive stars or leading into a final spectacle known as the supernova. It is a dramatic burst of radiation that can raise a star to become one of the brightest objects in our night sky. According to historical records, such was the case for example for the supernova seen in 1054. For the star itself supernova is a devastating process that rips its outer layers apart and leaves behind either a black hole or a crushed core, the neutron star (NS).

The observational history of NSs began in the 1960s with the discovery of regularly pulsed emission in radio waves from a source now known as PSR B1919+21 [1]. The discovery lead to intense discussions since the nature of the phenomenon was uncertain. The focus was especially on the length of the pulse period, 1.33 s, which is a very short time in the astronomical context. One possible explanation was related to another stellar remnant, which was already better known at that time, the white dwarf. Theoretically, the matter in these spherical objects could have oscillated and produced such radio pulses. However, Gold [2] among others suggested that the pulsations were radio emission from rotating NSs. This was confirmed when pulsars were later identified inside supernova remnants. For example, the gaseous remnant of the supernova of 1054, the Crab nebula was found to host a radio pulsar [3; 4]. Additionally, the pulsations of Crab pulsar occurred at the time scale of milliseconds, too fast for white dwarf oscillations.

Nowadays, it has been established that radio pulsars are indeed NSs which emit radio waves, powered by the NS's rotational energy. Observationally, the pulsations arise when the beam of radiation periodically sweeps over our line of sight, because the emitting regions at the NS's magnetic poles are not aligned with the NS's rotational axis. The picture is similar to a lighthouse.

NSs are very dense, with a mass of about 1.4 solar masses condensed into a sphere with a radius of 12 km. Their density is of the order of the atomic nucleus and the composition is rich in neutrons, hence their name. Interestingly, in the core of the NS, the state of the extremely dense matter is not known. This is one of the reasons NSs are important objects to study.

Fortunately for observers, in addition to isolated radio pulsars, NSs can appear with companion stars. This is because many massive stars, the NS progenitors, have normal companion stars, and some of these binary systems can survive the supernova explosion. The presence of a NS in a binary system becomes apparent especially if under suitable conditions, matter is transferred from the companion to the compact object. This follows from the fact that the accreted matter radiates efficiently in X-rays when falling onto the surface of the compact object. Similar to radio pulsars, the radiation comes mainly from the magnetic poles where the matter is guided. This means that NSs can also pulsate in X-rays like Cen X-3, the first X-ray pulsar that was discovered [5]. The characteristics of these systems can be studied extensively from the energy spectrum in X-rays and how the brightness varies with time, but the objects themselves are too small to be directly imaged.

The magnetic field is an important parameter for accretion. Similar to the internal composition, the magnetic field strengths of NSs are also extreme. Ranging from 10^8 to 10^{15} G [6], the field strengths are strongest in the universe and indeed far beyond what mankind can produce in laboratories. Consequently, certain phenomena related to how matter behaves in these magnetic fields can be studied best around NSs. One of the key questions concerns how such fields form when the stellar core collapses.

Unfortunately, the options for measuring the magnetic field strength are limited. The only direct method is the cyclotron line: when electrons move in a magnetic field, their energy states are quantized into Landau levels, and therefore they absorb at and emit photons with only the specific cyclotron energy and its harmonics, which produces an observable “absorption line” in the energy spectrum. The centroid energy of this feature directly corresponds to the local magnetic field strength. Her X-1 was the first source in which the feature was observed [7]. However, since the magnetic field strength measured from the cyclotron line is tied to the oftentimes unknown characteristics of the line-forming region in the vicinity of the NS, it is important to compare measurements made using other methods as well.

In this thesis, we present an additional, independent study of NS magnetic fields based on timing analysis of the X-ray flux variability. The variability originates in the accretion disc around a NS in a binary system and thus reveals the magnetospheric truncation of the disc. In the power spectrum, the truncation is seen as a characteristic frequency known as the break frequency. Measuring the break frequency thus gives information of the magnetic field further away from the NS and helps build a complete picture of the field structure and accretion processes.

2 X-ray pulsars

2.1 Formation of neutron stars

Ordinary stars form when a cloud of interstellar matter collapses under its own gravitation. The increasing core pressure ignites the nuclear fusion processes, initially combining hydrogen into helium. The fusion of elements releases energy in the form of radiation, producing an outwards pressure that supports the star against gravitational collapse. During the stellar lifetime, the elemental composition gradually changes and new cycles of fusion are initiated when the pressure and temperature of the core pass the required thresholds. Whether these conditions are met depends on the mass of the star, and in general, the more massive the star, the further the fusion continues.

For a main-sequence star above red-dwarf mass range, the change of stellar composition eventually halts the energy production when a new fusion cycle cannot be ignited. With no more fusion energy produced, the stellar matter collapses under its own gravitation. However, there are intermediate stages to the collapse, depending on the stellar mass originally supported. The first stage occurs when electrons in the core become very closely packed. As described by the Pauli exclusion principle, electrons cannot occupy the same state, which causes a degeneracy pressure that may inhibit the matter from further contraction. The remnants of stars which settle to this stage are called white dwarfs and their masses are below the Chandrasekhar limit of 1.4 solar masses.

For massive stars, fusion of elements can continue all the way up to iron. Iron is a turning point amongst elements since its fusion does not release energy any more. In a few millions of years, the composition of the core consequently becomes dominated by iron and the stellar energy production reaches a final standstill. With a core mass exceeding the Chandrasekhar limit, the star collapses, but this time, the gravitational pull of matter increases beyond what electron degeneracy can withstand. Consequently, the electrons combine with protons of atomic nuclei, forming neutrons and releasing electron neutrinos. While the infalling outer layers can somewhat bounce off from the compacting core, it is thought that in the end, the sudden, dramatic increase in the neutrino flow is what pushes the infalling layers off and the star explodes as a core-collapse supernova [8; 9]. For isolated stars with initial masses from 10 to 25 solar masses, the neutron-enriched core remains as a NS [10].

However, a more massive star can collapse further into a black hole. Instead of electron degeneracy, NSs are kept from collapsing by the neutron degeneracy pressure and strong nuclear force. This state might be reached from the white dwarf as well: a white dwarf composed mainly of oxygen and neon could collapse into a NS after accumulating mass beyond the Chandrasekhar limit, although these events remain yet undetected [see e.g. the review in 11].

At such a compactness, NSs exhibit intriguing phenomena of both general relativity and quantum mechanics, from light bending to quantised photon-particle interactions. Under the intense gravitational pull of the NS matter, the NS core composition reaches a state of matter unique to NSs and yet uncertain to us. Different models have been constructed to describe the equation of state and observationally, these can be constricted by measuring both the NS mass and the radius [12]. Various methods such as pulse profile modeling [13] and cooling tails of X-ray bursts [14; 15] have produced NS mass and radius values of about 1.4 $M_\odot$ and 12 km.

NSs are observed highly magnetized with field strengths ranging from 10^8 in old radio pulsars to 10^{15} G in magnetars [6]. At such a strength, the magnetic field substantially affects the movement of matter and how it interacts with radiation around the compact object. Mainly, matter falling onto the NS surface is confined to the magnetic poles. Based on pulsar observations, the structure of the magnetic field is typically a dipole, that is, having two magnetic poles on the surface of the NS.

The range of magnetic field strengths raises a major question of how the magnetic field forms and evolves onto such a wide scale. Simplistically, the field could be a fossil field: conserved magnetic flux that has been condensed from the initial stellar magnetic field during the collapse. This scenario, however, has its problems since the collapsing star loses its outer layers in the supernova so only a fraction of the initial field is likely to survive [16]. Additionally, the observed formation rate of magnetars does not agree well with the observed number of progenitor stars which are massive and highly magnetized enough. Therefore, the magnetic field is suggested to be strengthened during the NS formation by a dynamo process [17], that is, one of the various mechanisms of converting the kinetic energy of the fluid into magnetic energy [for a review of field formation, see 16]. With time, the field could then decay to the lower field strengths of old pulsars. This of course depends on the nature of matter inside the NS and how the magnetic field is generated, either confined to the crust or permeating parts of the core [6].

2.2 Binary systems

Many stars have companions and the probability of a star being a part of a binary system increases with stellar mass [see e.g. 18; 19; 20]. Born out of massive stars, many NSs thus form in binary systems. The mass of the companion star and the NS orbital parameters are important for the evolution and observational appearance of such objects. These parameters can be affected not only by the mass losses but also by the impulses or kicks caused by asymmetries in the supernova collapse [21; 22; 23]. Due to mass exchange during the ordinary stellar phase, the NS progenitors initial mass can also differ from the isolated case [23; 24].

Depending on the companion star's mass, binaries are divided into high-mass and low-mass systems. NSs orbiting a massive star in a high-mass X-ray binary (HMXB) system are typically observed as X-ray pulsars. HMXBs are young systems since massive stars are short-lived. On the contrary, low-mass systems are likely to be old. Such X-ray sources appear as low-mass X-ray binaries (LMXBs), or as accreting millisecond pulsars (AMPs) in which the NS has been spun up to a millisecond-range period by accretion from the companion. The companion mass determines many characteristics of the NS system such as whether mass exchange takes place and how it proceeds.

Accretion has two primary paths onto the compact object: directly from stellar wind or via an accretion disc around the compact object [25; 26]. These are illustrated in Fig. 1 after Shakura and Sunyaev [27]. If the companion star is very massive, its stellar wind may be dense enough for accretion to release measurable quantities of X-ray radiation. In the Bondi-Hoyle-Lyttleton model, the orbiting NS shocks the wind medium, forming an accretion wake inside which the matter settles onto the NS. In LMXBs systems, by contrast, the companion star typically fills its Roche lobe, the 3-dimensional volume inside which matter is bound by gravity. Therefore, the stellar matter can overflow into the potential well of the NS through the inner Lagrange point L1 where the Roche lobes of the binary stars meet.

In this thesis, the prime example of a disc-accreting LMXB is the source known as GRO J1744$-$28 which has a magnetic field of $\approx 5 \times 10^{11}$ G in between the populations of AMPs and X-ray pulsars [28]. The highly luminous system also shows accretion-related X-ray bursts but no thermonuclear bursts originating to the surface of the NS [29]. It was suggested that the system could be a pulsar currently being recycled into an AMP, although the nearing exhaustion of the companion's envelope may leave the final pulse period still rather long [30]. Any radio pulsations from the system in quiescence are yet to be observed [31].

The fast rotation of massive Be stars can also serve as a source of matter for compact companions: when the centrifugal force on the stellar equator is of the same magnitude as the gravitational pull of the star, matter can spread into a decretion disc. This is evident as emission lines in the stellar spectrum. An accompanying NS on an eccentric orbit may then periodically capture some of the decretion disc near the periastron. Accretion of this matter leads to intermittent outbursts in which the source brightness can increase by several orders of magnitude. A classic example of such a transient system is 1A 0535+262.

On the other hand, persistent accretors are observed always accreting and emitting, sustained by the companion's mass outflow. GX 301$-$2 is an example of such a

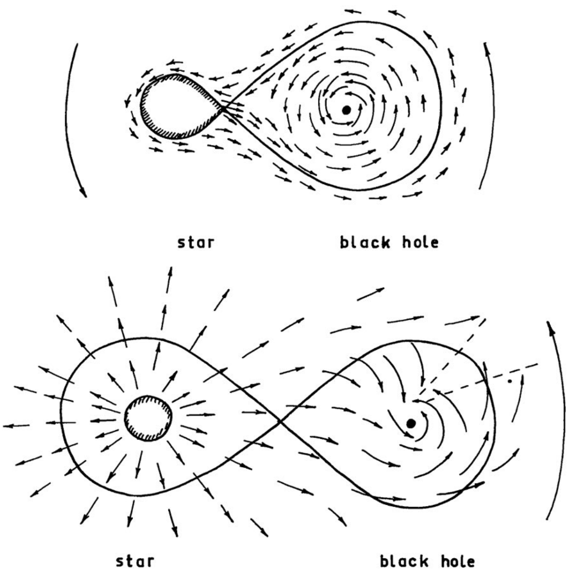

Figure 1. A schematic of the two primary accretion scenarios: Roche-lobe overflow leading to the formation of an accretion disc and strong wind of the companion from which the compact object accretes. Courtesy of Shakura and Sunyaev [27].

system which is accreting mainly from the companion's stellar wind. While the NS is rotating slowly, from time to time, the NS is seen to spin up, most likely powered by episodes of disc accretion. Her X-1 is a persistent system in which an accretion disc forms. The system is viewed rather edge-on so the companion star occults the NS with a period of 1.4 days. Additionally, the accretion disc is warped and obstructs the X-ray emission from the NS with a super-orbital period of about 25 days [32]. Long-term observations of such systems are useful for studying NS systems and testing models for mass accretion.

3 Accretion onto highly magnetized neutron stars

Accretion of matter onto a compact object is an efficient way of transforming potential energy of matter into radiation. Consequently, accreting objects are observed over the entire electromagnetic spectrum, with the dominant energy ranges depending on the nature of the object. In this work, we focus on the X-rays released by energetic particles in the vicinity of a highly magnetized NS. Of specific interest is the temporal variability of their X-ray intensity known as the X-ray light curve which can be used to study the ongoing processes in these systems as well as their long-term evolution.

3.1 Accretion disc

Due to the angular momentum of the matter captured by the NS, it cannot be directly accreted onto the surface. Instead, the matter first settles onto a circular orbit around the NS. From there, viscous processes enable the transport of angular momentum outwards with a fraction of the mass while majority of the matter is able to spiral towards the NS, spreading into an accretion disc [33]. In their seminal accretion disc model, Shakura and Sunyaev [27] formulated the α parametrisation for the unknown source of viscosity and with it, could derive the disc structure. Later, the magneto-rotational instability (MRI) was suggested as the source of viscosity [34]. In the MRI model, the local magnetic field ties parts of the differentially rotating accretion disc together like a spring which opposes the growing distance between the connected disc elements. However, the acceleration of the outer, slower element only acts to further increase the distance. This causes mixing of the disc matter, transporting angular momentum outwards.

As a whole, the matter in the accretion disc orbits the NS with a more or less Keplerian angular velocity

$$\omega_{\mathrm{K}}(r) = \sqrt{\frac{GM}{r^3}}, \tag{1}$$

where G is the gravitational constant, M mass of the NS and r the radius of the orbit around the NS. The velocity of the disc matter increases towards the central object and the interaction of disc matter with itself transforms kinetic energy into heat. Therefore, the disc temperature increases towards the central object and the structure of the disc becomes dependent on the distance from the central object.

The Shakura-Sunyaev disc model posits that the dominant interactions can be used to classify the various radial zones of the accretion disc: In the outermost zone C and in the one inside it, zone B, the disc height is supported by the pressure of the accreted gas. These two zones are differentiated, however, by the main contribution to the opacity, which in zone B comes from electron scattering and in zone C from free-free absorption among others. In case the accretion rate is high enough, an innermost zone A may form. The electron scattering opacity continues to dominate in the zone A but the pressure there is mostly provided by radiation. The physical thickness of the disc increases outwards from the compact object and in zone A, the disc is the most “puffed-up”, with thickness relative to the distance from the compact object being greater than in the outer zones. The topics were revisited by Suleimanov et al. [35] who concluded that the suggested hot corona above the accretion disc actually plays an important role for the observations of disc thickness.

3.2 Magnetosphere

When matter falls towards a highly magnetized NS, at some point, the magnetic field is strong enough to capture the matter, guiding it along the field lines onto the magnetic poles. This distance in spherically uniform accretion is the Alfvén radius $R_{\rm A}$ which can be calculated by equating the magnetic pressure with the ram pressure of the infalling gas. In the context of an accretion disc, the radius where the disc is disturbed is known as the magnetospheric truncation radius:

$$R_{\rm m} = \Lambda R_{\rm A} = 2.6 \times 10^{8} \Lambda m^{-1/7} R_6^{10/7} B_{12}^{4/7} L_{37}^{-2/7} \text{ cm}, \tag{2}$$

where Λ is the parameter describing the geometry of the accretion flow: for wind, $\Lambda = 1$ and for accretion disc it typically is chosen as $\Lambda = 0.5$ based on theory and observations [see e.g. 36; 37]. Furthermore, m is the NS mass in solar masses, R is the NS radius, B is the magnetic field strength and L the luminosity. Throughout the thesis we use the subscript notation for unitless quantities with $Q = 10^x Q_x$ in cgs units. In summary, the magnetospheric radius decreases when the increasing mass accretion rate is able to push the disc against the magnetic pressure of the NS magnetosphere.

The extent of the magnetospheric radius governs various aspects of accretion. Firstly, for accretion to proceed, the disc matter at the magnetospheric boundary must have an angular velocity greater than the magnetosphere, that is, the magnetospheric radius must be smaller than the corotation radius, where the angular velocities are equal:

$$R_{\rm co} = \left(\frac{GMP^2}{4\pi^2} \right)^{1/3}, \tag{3}$$

where P is the spin period of the NS. The remaining angular momentum in the disc is transferred to the NS at the magnetospheric radius, which accelerates the rotation of the NS [25; 36]. When the magnetospheric radius is close to the corotation radius, the system is accreting in equilibrium. Otherwise, if the magnetospheric radius exceeds the corotation radius, the accretion becomes centrifugally inhibited, entering the ”propeller” regime [38]. The magnetospheric radius of a pulsar can change during an outburst such that the system changes from an accretion regime to another. Evidently, during the decline of an outburst in some sources, the luminosity may be seen to drop dramatically below a certain luminosity at which the magnetospheric radius is thought to reach the corotation radius [see e.g. 39]. This then allows for the measurement of the magnetospheric size.

In the extreme end of magnetospheric size are NSs with magnetar-scale magnetic field ranging from 10^{13} to 10^{15} [6]. It has been suggested that these objects may also reach very high luminosities and appear as the pulsating ultra-luminous X-ray sources (ULXs) [40; 41; 42]. There are complications to this picture, though, as according to Israel et al. [43], accretion in the ULX NGC 7793 P13 would be prevented by the propeller effect if the global field was of magnetar-scale strength. Instead, they suggested that the magnetic field is globally weaker but multipolar components at the foot of the accretion column allow the high observed luminosity. This effect was studied in more detail by Brice et al. [44] and in their model, the additional multipole components in the magnetic field indeed increase the maximal luminosity that can be reached by the pulsar. Additionally, the multipolar magnetic field components decay faster with distance so an accretion disc around a NS with a non-dipolar magnetic field is truncated closer to the NS as compared to the dipole case.

3.3 Emitting region

The accretion processes are specifically connected to various radiation mechanisms. In the accretion disc, the heated gas radiates locally similarly to a black body, and the total spectrum is a sum of these over the disc radii [27]. For stellar-mass black holes, the disc temperature rises high enough for the thermal radiation to be observed in the X-ray range. On the other hand, near the black hole, matter disappears without much radiation since the compact object has no surface. For NSs, the picture is different in two main aspects: the object has a surface and the accretion disc is truncated further out by the magnetic field of the NS. Therefore, the largest contribution to a NS’s emission comes from the hotspots at its magnetic poles, where X-rays are produced as braking and cyclotron radiation of the infalling plasma. The beaming of X-rays from these polar hotspots has important observational consequences: if the magnetic poles are offset from the rotation axis, the direction of the X-ray beam changes with the NS rotation. Thus a distant observer sees pulsars with a periodically pulsed emission pattern.

The accreting area on the surface of the NS depends on the accretion geometry [45]. For wind-accretors, the spherically accreted matter fills the funnel entirely. Alternatively, when matter is accreted from a disc, the flow forms an annulus or an arch on the surface. The shape of the emitting region then depends on the accretion disc thickness and how deep into the magnetosphere the accretion disc penetrates. At low mass accretion rates, the funneled flow of matter settles more or less directly onto the NS surface, forming hotspots on the magnetic poles. The more matter is accreted onto the hotspot, the more X-ray radiation is released. Locally, above a certain mass accretion rate, the released emission can then even counteract the gravitation acting on the infalling matter. Above this critical luminosity, the infalling matter is decelerated already above the surface, which leads to the formation of an accretion column [45]. The characteristics of the column are affected by how the strong magnetic field changes the opacity of the medium [46].

The various components that contribute to the continuum emission, blackbody radiation of the hotspot, braking radiation of the accretion flow (bremsstrahlung) and cyclotron radiation in the magnetic field are all Compton up-scattered by the energetic particles to form a spectrum reminding a cut-off power law [see e.g. 47]. Fitting the energy spectrum and integrating the model over an energy band allows us to measure the flux F. When the distance D is known, the flux can be converted to the luminosity with $L = 4\pi D^2 F$. The luminosity is further related to the mass accretion rate $\dot{M}$ through $L = GM\dot{M}/R_*$ with the size of the compact object R_*. NSs are interesting as they can reach mass accretion rates that exceed the Eddington luminosity limit $L_{\mathrm{Edd}} = 1.26 \times 10^{38} m$ erg s^{-1} which would disrupt spherical accretion.

In the strong magnetic field of NSs, the motion of electrons is quantised, leaving them to absorb and emit photons with only specific energies in the X-ray range. The result can be observed as a cyclotron resonant scattering feature (CRSF), or a cyclotron line. This absorption-like dip in the continuum has a width due to the velocity distribution of electrons. The centroid energy of the primary feature is

$$E_{\mathrm{cycl}} = 11.6 B_{12} (1+z)^{-1} \mathrm{keV}, \tag{4}$$

where z is the relativistic gravitational redshift related to NS mass M and radius R as $1+z = (1-2GM/c^2R)^{-1/2}$ [see 48, for a recent review on the CRSF]. Detecting E_{cycl} is the only direct method of measuring the magnetic field strength.

Observationally, the CRSF also depends on the source luminosity with a bimodal behaviour: at low luminosities, the line centroid energy has a positive correlation with luminosity [49; 50] while above the critical luminosity, the correlation changes to negative [51; 52; 53; 54; 55]. This has been connected to possible physical changes of the accretion structures on the NS surface and their X-ray beam characteristics: the positive correlation is related to accretion onto the hotspot while above the critical luminosity of accretion column formation, the correlation would change to negative [56; 46]. The magnetic field strength and the structure of the magnetosphere are key parameters that determine the accreting area of the hotspot and thus the critical luminosity. Conversely, measuring the critical luminosity provides another way of estimating the magnetic field strength. To date, the critical luminosity has been observed in only two sources, V 0332+53 [57; 55] and 1A 0535+63 [58]. However, the observations of additional temporal evolution of the cyclotron energy revealed that the connection of the cyclotron line to magnetic field is not trivial. Additionally, Her X-1 shows a positive luminosity-correlation of the CRSF at an unexpectedly high luminosity [42]. Therefore, other, indirect methods are required to form a complete picture of a NS magnetic field.

Connecting the cyclotron energy to the global magnetic field can be complicated by various factors: the CRSF formation region is affected by the accretion of matter on the polar regions because it changes the organization of field lines. The foots of field lines are compressed together which locally increases the field strength and affects especially the phase-dependence of CRSF [59]. The deformed field can be described by an expansion of the dipole moment with multipolar components with various offsets. Observed CRSF harmonics with non-integer ratios may be a sign of these non-dipolar field components [60; 61]. Old pulsars are likely to have accreted matter during their lives and could be good candidates of observing a deformed magnetic field. Alternatively to the gradual formation, it has been suggested that the magnetic field could directly form as multipolar [6] and persist for long times if the magnetic field is confined to the NS crust [62]. The implications of the shape of the multipolar field were discussed to some extent by Lipunov [63]. The assumption of a centered, dipolar magnetic field configuration has been relaxed in several studies of isolated NSs [64; 65; 66; 67; 68].

Importantly, the multipole components affect the accreting regions on the NS surface: for a purely quadrupolar magnetic field, a cusp in the field surrounds the equator, allowing for equatorial hotspots in addition to the two accreting regions of an ordinary dipole. If the magnetic field is an asymmetric mixture of dipolar and quadrupolar components, an accreting annulus occurs further from the pole than in the standard disc accretion scenario [see e.g. 69; 70; 71; 72]. Several studies of the complex pulse profile of the LMXB Her X-1, including Shakura et al. [70] and Postnov et al. [73], have suggested that the magnetic field structure is such an asymmetric quadrupole. The potential multipolar configuration can also solve the mystery of the higher than expected critical luminosity in Her X-1: the accreting areas would be expected to be larger in the multipole case than in the dipole case which consequently allows for the high critical luminosity.

There can be a large discrepancy between the size of the magnetosphere expected from the CRSF and the magnetospheric radius measured by other means. Partly, this disparity arises because these methods map the magnetic field at different distances from the NS. Combining independent examinations is required to form a complete picture of the structure of the magnetic field. In the next chapter, we utilize the fact that while the emission comes mainly from the vicinity of the NS, it carries a temporal imprint of the accreting system.

4 Mapping the magnetosphere

Various spectral and temporal analysis methods can be used to study the accreting systems and the magnetic field of the NSs. The change in the pulse period is a useful tool linking the NS rotation to the torque which is largely affected by the magnetospheric radius. Consequently, spin-up models can be used to constrain the magnetic field strength [36]. Details of spin evolution linked to accretion geometry were discussed and utilized in Papers I and II in the study of the both wind-fed and disc-fed system GX 301$-$2. In this chapter, we will delve further into what the X-ray variability can reveal of the accretion disc and the magnetosphere.

4.1 Propagating fluctuations in the accretion disc

The observed X-ray light curve of an accreting compact object usually shows variability on a wide range of time scales, from hours to milliseconds. In addition to the periodic signals of NS pulsations and binary orbit, the flux variability has various other features such as quasi-periodic oscillations. The main focus of this thesis is, however, what lies beneath all these phenomena: the widely distributed continuum of variability whose origin has also been connected to the accretion disc.

Let us first note that the variability in the X-ray light curve can be conveniently studied in the frequency domain, through the power density spectrum (PDS). The PDS is based on the Fourier transform of the time series which allows us to see the periodicities and compare how strongly the flux varies in different frequency ranges. Hoshino and Takeshima [74] made a major discovery in this regime by observing that the PDS of accreting, strongly magnetized NSs takes the shape of a broken power law with the break to a steeper power-law index occurring around the pulse frequency. They argued that the flux variability is connected to the density fluctuations of the accretion flow falling onto the NS. More specifically, Hoshino and Takeshima explained the two power-law regimes by turbulence excited by the rotation of the magnetized NS.

Lyubarskii [75] suggested that the power-law noise in the X-ray flux, which was argued to originate from the regions close to the compact object, can be explained as a sum of viscous processes occurring throughout the accretion disc: local variation in the viscosity parameter α affects the redistribution of angular momentum and thus perturbs the local mass accretion rate, in such a manner that the independent fluctuations from different disc radii can be summed into the total mass accretion rate at the inner radius. This model, in which the diffusion of fluctuations is governed by Green functions, produces a PDS distribution of power with a slope having an index around -1. The exact value of the index depends on the relation of α variations to the disc radius. Stronger variability at larger radii produces more power at low frequencies.

Churazov et al. [76] studied the black hole system Cyg X-1 and continued the development of the perturbation propagation model, especially connecting the origin of viscosity fluctuations to the magneto-rotational instability [34]. The variability at frequencies higher than the local viscous frequency was shown to be dampened in a geometrically thin disc while in a thick disc, more high-frequency variability would survive to the emitting regions.

Uttley [77] considered how the root mean square (rms) variability of the flux is linearly related to the flux in perturbation propagation models and saw this also in the pulsed flux of an accreting millisecond pulsar SAX J1808.4$-$3658. Additionally, they found a correlation in the amplitude of aperiodic variability and rms of the pulsations. This confirmed that while the X-ray emission comes from the compact emitting regions at the magnetic poles, the aperiodic variability of the accretion flow originates from the entire accretion disc. Therefore, the imprint of the disc system can be seen in the PDS.

Revnivtsev et al. [78] continued on the tracks set by Hoshino and Takeshima [74] and compared break frequencies of several pulsars. They focused on objects accreting in equilibrium, that is, their magnetospheric radius coincides with the corotation radius. The study showed that in these sources, the break frequency coincides with the pulse frequency, suggesting that the maximal variability generated in the disc corresponds to the Keplerian frequency at the magnetospheric radius of the accretion disc. The theoretically expected luminosity-dependence could be measured as well. The accretion discs around magnetized white dwarfs in systems known as intermediate polars were found to show the same connection between the aperiodic noise of their optical light curve and their disc truncation [79]. Importantly, this means that through the magnetospheric radius the break frequency translates into an estimate of the magnetic field strength independent from the cyclotron line.

Mushtukov et al. [80] presents a model for the generation of broad-band aperiodic variability, examining the effects of viscous diffusion. By the nature of these stochastic processes, further away from the NS, the amplitude of variability is larger and the time scale longer, linked to the Keplerian orbital frequency. The arising perturbations spread in the disc both inwards and outwards so that they are accumulated from the entire disc to its inner edge. From there, they are conveyed in the mass flow along the magnetic field lines and onto the surface of the NS. The X-rays produced on the surface vary with the mass accretion rate fluctuations, resulting in the red noise seen in PDS. Due to the truncation of the accretion disc, no additional per-

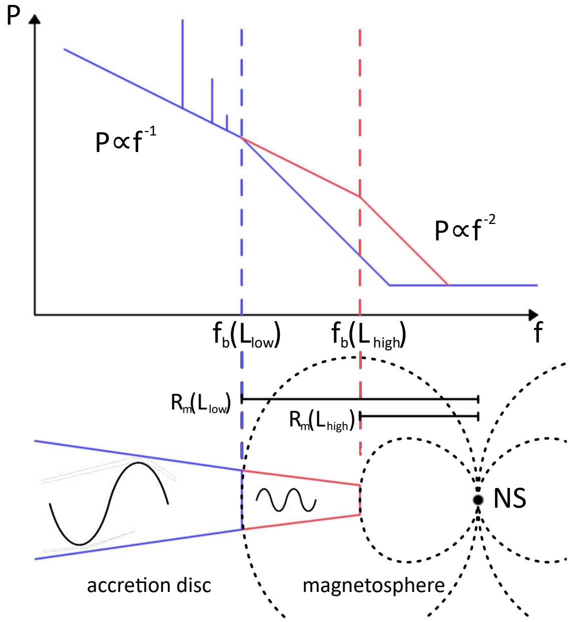

Figure 2. A schematic of how the power density spectrum of an accreting highly magnetized neutron star (NS) is connected to the accretion disc. The break frequency is connected to the fastest variability at the inner radius of the magnetospherically truncated accretion disc. At low luminosities, the disc is truncated further away from the NS which results in a lower break frequency (blue). When the luminosity and thus the mass accretion rate increases, the disc penetrates deeper into the magnetosphere and the break frequency appears at a higher frequency (red). The variability that is generated in the outer disc is slower and stronger than in the inner disc, which superpose into the power-law variability of $\mathrm{P} \propto \mathrm{f}^{-1}$. Examples of the spikes of regular pulsation and its harmonics are shown in the PDS as well.

turbations are generated within the magnetosphere so the red noise dependence of $\sim f^{-1}$ breaks to a steeper power-law of f^{-2}. The break occurs at the frequency of the fastest initial variability for noise generation at the inner radius of the accretion disc. The connection between the accretion disc and the PDS is illustrated in Fig. 2.

The maximal frequency generated in the disc ought to be the Keplerian frequency at the innermost disc radius. To find how the Keplerian frequency at the magnetospheric radius depends on the system parameters, we substitute equation (2) into the expression for orbital frequency $f_{\rm K}(r) = \omega_{\rm K}(r)/2\pi$ with $\omega_{\rm K}(r)$ given in equation (1):

$$f_{\rm K,m} \simeq 0.1\,\Lambda^{-3/2} m^{5/7} \dot{M}_{16}^{3/7} \mu_{30}^{-6/7}\ \mathrm{Hz}, \qquad (5)$$

where $\mu = BR^3$ is the magnetic moment. Assuming that the break is related to $f_{\rm K,m}$ and mass accretion rate is directly proportional to luminosity, the prediction is that the break frequency depends on the luminosity as $f_{\rm b} \propto L^{3/7}$. Revnivtsev et al. [78] confirmed that the prediction holds for 1A 0535+262, adding further evidence in favour of the theory.

4.2 Data analysis

Rossi X-ray Timing Explorer (RXTE) was a cosmic X-ray observatory launched in 1995 and decommissioned in 2012, gathering a great wealth of high-quality data. The satellite housed two large-area instruments with a wide, one-degree field of view: Proportional Counter Array (PCA) and High-Energy X-ray Timing Experiment (HEXTE). In my thesis work, I have focused of the PCA observations which reached a very good time resolution of ~ 1 μs in the energy band $2 - 60$ keV. The working principle of PCA was counting photons in its five Proportional Counter Units (PCUs) based on ionizing reactions in the xenon gas [81]. X-ray light curves were reduced from the data files following standard procedures.[1]

In the analysis, the time constraints of the data determine which frequencies of variability can be recovered from the time series. The time resolution of the measurement Δt sets the highest frequency that can be measured, the Nyquist frequency: $f_{\rm Ny} = 1/(2\Delta t)$. At the other end of the PDS, the lowest measurable frequency relates to the duration of the time series T as $f_{\rm min} = 1/T$. All the measurements rely on the fact that the signal can be recovered from the statistical noise with certainty. The counting of the photons by the instrument is affected by the randomness inherent in the radiation processes and thus the photon arrival times. Characterized by the Poisson process, this produces a level of white noise which has to be subtracted in the analysis. To decrease the standard deviation of the power estimates on all scales initial power spectra from parts of the time series are averaged together. Averaging also ensures that the data can be taken to be normally distributed and χ^2 statistics can be used in the analysis [82]. Otherwise, the best option is to use the Whittle statistics on data for which a constant number of points has been binned together. For an explanation of how the Whittle statistics can be utilized in maximum likelihood estimation, see Vaughan [83].

Optimally, the break frequency can be used to estimate the magnetic field strength in sources where other methods such as the CRSF do not give conclusive results. For measuring the break frequency, we simplistically took the underlying aperiodic noise to follow a broken power law:

$$\bar{n}(f) = \begin{cases} f^a, & f < f_{\rm b} \\ f_{\rm b}^{a-b} f^b, & f \geq f_{\rm b}. \end{cases} \tag{6}$$

Paper III presents how the break frequency method was utilized for the source known as Swift J1816.7−1613. However, no break frequency could be measured in the PDS since the high frequencies were dominated by the Poisson noise. Nevertheless, the

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[1] `https://heasarc.gsfc.nasa.gov/docs/xte/recipes/cook_book.html`

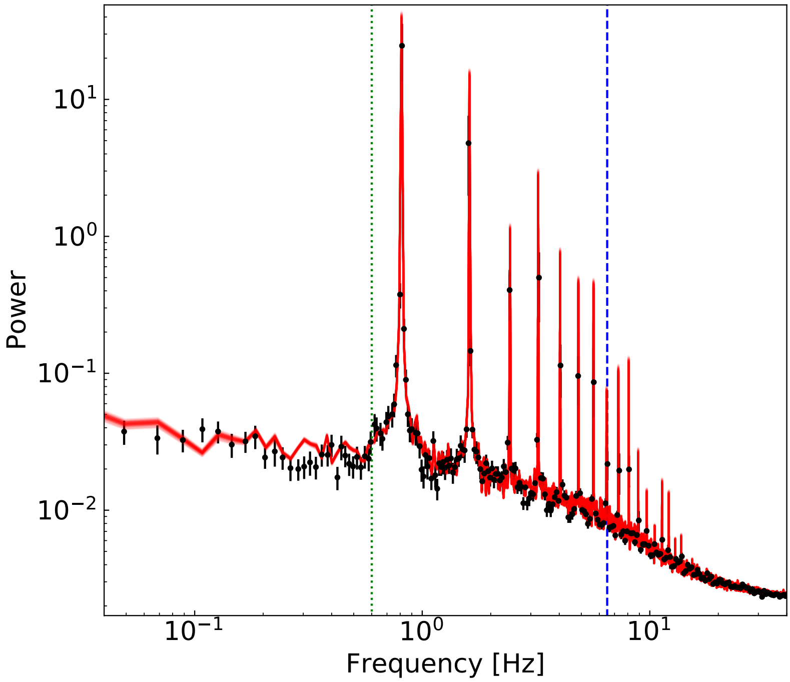

Figure 3. Power density spectrum of Her X-1 with the model with parameter sets from a random selection of best-fit Markov Chain Monte Carlo runs. The convolution of pulse shape with the aperiodic variability was taken into account to fit the wings of pulsations better. The green dotted vertical line shows the position of the break expected from CRSF while the blue dashed vertical line shows the best model-fit break frequency.

non-detection helped limit the magnetic field strength together with other considerations.

In Paper IV, we noticed that the PDS of GRO J1744−28 deviates from the broken power law, having two ”humps” instead. We argued that due to the high mass accretion rate, the inner accretion disc becomes radiation-pressure dominated (zone A) [27]. This changes how the noise is dampened, strongly reducing the low-frequency variability and allowing more high-frequency variability to survive. For truncation in this region, the luminosity-dependence of the magnetospheric radius is expected to change as well, and we indeed could not observe the basic $f_\mathrm{b} \propto L^{3/7}$. Additionally, the break frequency was found to be much higher than expected based on the CRSF.

Paper V reports that a similarly high break frequency was found also in Her X-1. However, in this source, the break frequency was hidden beneath the harmonics of the regular pulsations. Lazzati and Stella [84] had specifically addressed the pulse modulation of the aperiodic noise and shown that it could affect the measurement of the break frequency. Therefore, to confirm that the deviation of the break frequency

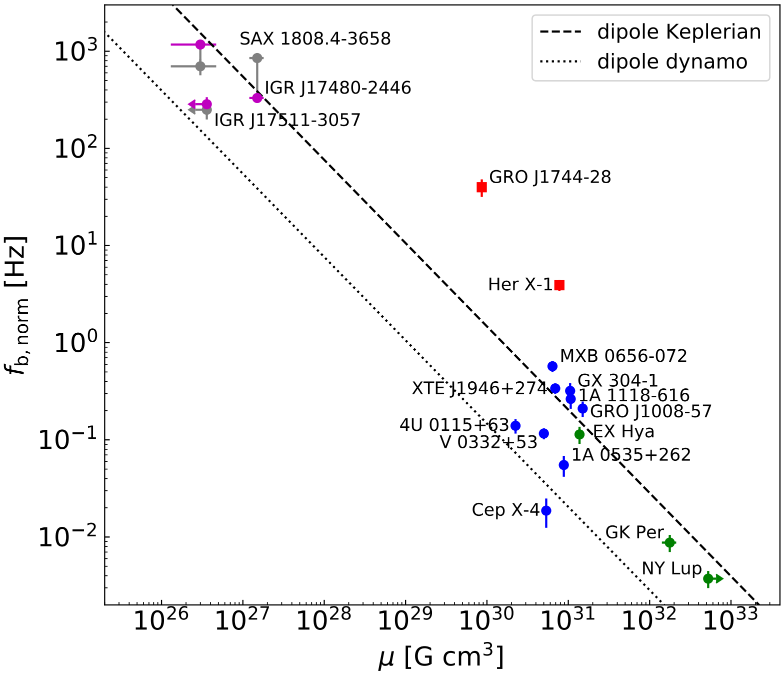

Figure 4. Normalized break frequencies of various sources plotted against their magnetic moments. The normalization allows objects with different masses and mass accretion rates to be compared. Most objects obey the theoretically expected behaviour, simply the Keplerian frequency at the innermost radius of the accretion rate. However, two LMXBs, GRO J1744−28 and Her X-1 stand out for having a much higher break frequency than the standard dipole magnetic field configuration would entail.

was not an artefact of inadequate analysis, we considered the modulation effect. We did not find notable difference from the simple broken power law so the unexpectedly high break was argued to be of physical origin. Fig. 3 shows the model fits to the PDS of Her X-1. The fits reveal that the break frequency is preferably ten times higher than what is expected based on the CRSF.

Setting a common ground for the results, Paper V compared several accreting pulsars and white dwarfs within the framework of the perturbation propagation model. When the break frequency is normalized to account for the differences in the size of the object and the mass accretion rate at the time of the measurement we are left with the dependency only on the magnetic moment as $f_{\rm b,norm} \propto \mu^{-6/7}$. In Fig. 4, we see that the objects in our sample indeed obey the same principles of accretion except for two outliers, GRO J1744−28 and Her X-1. Various sources of error were seen unable to explain such a large discrepancy. Considering the literature on the complex magnetic field structure in Her X-1 [70; 73], we suggested that a multipolar magnetic field configuration is the most likely explanation for the high break frequency.

5 Summary and future of research

Timing analysis of X-ray light curves of accreting compact objects is crucial for understanding accretion and how matter interacts with the magnetic field. In this thesis, X-ray pulsars were studied on a wide range of time scales and several cases of unusual behavior were discussed and explained. One of these is the object known as GX $301-2$, where the orbital variability on long time scales revealed for the first time that the NS rotates retrograde with respect to its binary orbit. Short time scales, on the other hand, correspond to the regions close to the compact object.

Combining various direct and indirect methods of estimating the magnetic field strength helps eliminate possible caveats of using only a single method and allows gaining insight into the nature of the magnetic field of a compact object. Since the accretion disc and especially how far it penetrates into the compact object's magnetosphere affect the resulting X-ray variability, PDS offer a good tool for studying the system. Specifically, the break frequency can be used for studying the disc-magnetospheric interface when measured together with the cyclotron line and studied along with possible signs of the accretion disc in the energy spectra.

In this thesis, we have shown that the break frequency follows the same principles in both NSs and white dwarfs and allows estimating the magnetic moment. Furthermore, we have relaxed the common assumption of a dipolar magnetic field configuration, noting that a multipolar magnetic field may help explain the higher-than-expected break frequency of two pulsars, Her X-1 and GRO $J1744-28$. The possibility of a complex magnetic field structure should indeed be taken into account when building a picture of the disc-magnetospheric interaction.

In order to fully utilise the break frequency in measuring the magnetic field, it is important to understand why different sources differ from the predicted behavior. A further study could for example shed light on the connections of the break frequency, PDS shape and NS inclination with respect to the disc, if possible to estimate. Specifically, a model for the power spectrum more rooted in the complex physical environment will help connect the observed parameters to the physical quantities and compare various theories of the magnetospheric truncation of the accretion disc.

Accreting objects are also sources of polarized radiation. The future and now ongoing X-ray polarimetry missions will therefore widen the study of magnetized NSs and their accretion. Specifically, a phase-resolved study of pulsar polarization could help distinguish between "pencil" vs. "fan" beam patterns and their origins in the hotspot or the accretion column [85]. Additionally, abrupt changes in the polarization parameters would be a signal of non-dipolar field structure [86]. The reflection of X-rays from accretion disc and companion star could also be studied [85]. Even though long-term campaigns are required, the prospects for understanding systems such as Her X-1 are good. Notably, initial results are already arriving, as is signified by the measurement of the polarization degree and angle of Her X-1 using Imaging X-ray Polarimetry Explorer (IXPE) [87].

6 Summary of Original Publications

6.1 Paper I – NuSTAR observations of wind-fed X-ray pulsar GX 301−2 during unusual spin-up event

The persistent pulsar GX 301−2 was caught in our NuSTAR observations during its strongest spin-up event measured by *Fermi* Gamma-ray Burst Monitor (GBM). The constant spin-up is a clear indication of steady torque provided by a transient accretion disc forming around the NS. However, comparison to earlier NuSTAR observations showed that during our observation, majority of the radiation still originated to the wind accretion. The two cyclotron lines were detected in the energy spectrum and were measured to be positively correlated with luminosity, which can be a sign of accretion mount being below the critical luminosity of accretion column formation. The difference between the cyclotron lines remained fractional and varied along the pulse phase.

6.2 Paper II – Discovery of a retrogradely rotating neutron star in the X-ray pulsar GX 301−2

In this work, we studied the NS spin-up variability along the binary orbit in GX 301−2 and concluded that the NS rotates retrogradely with respect to its orbit. The discovery was based on the accretion stream model developed for the system in the literature and a simple geometric consideration of torque transfer. Most notably, the torque is not directly correlated with the flux during periastron flare, but changes from spin-up to spin-down while the NS passes through the accretion stream. Based on analytic consideration of the accretion torque, we fit a phenomenological model to the observed accreted angular momentum as function of orbital phase. The measured change of sign differs from the one expected for a progradely rotating NS, implying that the NS has a retrograde spin. The discovery helps explain the long spin period of the source and confirms for the first time that retrograde NSs exist as predicted in studies of supernova kicks. This has consequences for population studies of accreting pulsars as well as progenitors of gravitational wave sources.

6.3 Paper III – Properties of the transient X-ray pulsar Swift J1816.7$-$1613 and its optical companion

In this work, we studied the X-ray pulsar Swift J1816.7$-$1613 during the tail of its outburst to find or constrain its magnetic field strength. No cyclotron line was seen in energy spectrum nor break frequency in PDS. However, using the IR observations to limit the nature of the optical companion and the system distance from us, we could use the lack of cyclotron line and break frequency to set an upper limit to the magnetic field strength. Further limits came from not observing the transition to a propeller regime, instead seeing a possible transition to accretion from a cold accretion disc.

6.4 Paper IV – Evidence for the radiation-pressure dominated accretion disk in bursting pulsar GRO J1744$-$28 using timing analysis

In this paper, we examined the high-frequency flux variability of the bursting X-ray pulsar GRO J1744$-$28. The intriguing object has a magnetic field strength of 5×10^{11} G and accretes with a super-Eddington rate. The pulsar also exhibits brief type II bursts related to accretion instabilities. Judging by the luminosity, the inner accretion disc should be radiation-pressure dominated (RPD) zone A of a standard Shakura & Sunyaev accretion disc not usually seen around highly magnetized NS. We see that the power spectrum of the object has a distinguished shape which we qualitatively explain by developing a model for noise generation and propagation to account for the presence of the RPD region. We also measure the break frequency to be much higher than what is expected based on the magnetic field strength derived from the CRSF. This implies that the disc truncation radius is unexpectedly small, which we suggest to be related to the magnetic field being dominated by its quadrupolar component.

6.5 Paper V – Constraints on the magnetic field structure in accreting compact objects from aperiodic variability

The paper utilizes the work of Revnivtsev et al. [78, 79], who showed that the break frequency observed in magnetized accreting compact objects is connected to the magnetic truncation of the accretion disc. We extend the analysis to low magnetic moments of accreting millisecond pulsars and to high magnetic moments of intermediate polars and show that the basic phenomenon is shared between all these sources. Presenting the connection between the break frequency and source magnetic moment measured from the cyclotron line, we note a clear deviation from expectations in two sources, Her X-1 and GRO J1744−28. Based on literature on the possibility of multipole components in the magnetic field of Her X-1, we discuss how such a complex field structure would indeed reduce the magnetospheric radius and increase the break frequency.

6.6 The author's contribution to the publications

Paper I – NuSTAR observations of wind-fed X-ray pulsar GX 301−2 during unusual spin-up event

The author was the PI of the observations, contributed to the idea and worked on the introduction and discussion parts of the manuscript. The article will also be used in the doctoral thesis of Armin Nabizadeh.

Paper II: Discovery of a retrogradely rotating neutron star in the X-ray pulsar GX 301−2

The author was behind the idea, reduced and analyzed the data and produced the manuscript together with coauthors.

Paper III – Properties of the transient X-ray pulsar Swift J1816.7−1613 and its optical companion

The author studied the X-ray light curve through power spectral analysis, fitting with a broken power law to limit the break frequency value. The author also contributed to the manuscript on relevant parts, that is, section 3.3 and parts of the discussion. The article will also be used in the doctoral thesis of Armin Nabizadeh.

Paper IV: Evidence for the radiation-pressure dominated accretion disk in bursting pulsar GRO J1744−28 using timing analysis

The author reduced and analyzed the data and wrote the manuscript with coauthors' contributions.

Paper V: Constraints on the magnetic field structure in accreting compact objects from aperiodic variability

The author did the data reduction and analysis with coauthors' contributions and produced the manuscript together with coauthors.

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