

# Astro2020 Science White Paper: The Physics of Accretion Onto Highly Magnetized Neutron Stars

**Thematic Area:** Formation and Evolution of Compact Objects

**Principal Author:** **Michael T. Wolff**, Space Science Division, Naval Research Laboratory, Washington DC 20375, USA, Email: Michael.Wolff@nrl.navy.mil, Phone: (202) 404-7597

**Co-authors:**

**Peter A. Becker**, George Mason University, Fairfax, VA 22030, USA

**Felix Fürst**, European Space Astronomy Centre, Villanueva de la Cañada, Madrid, Spain

**Sebastien Guillot**, Institut de Recherche en Astrophysique et Planétologie, Toulouse, France

**Alice K. Harding**, NASA Goddard Space Flight Center, Greenbelt, MD 20771, USA

**Paul B. Hemphill**, MIT Kavli Institute, Cambridge, MA 02139, USA

**Gaurava K. Jaisawal**, National Space Institute, DK-2800 Lyngby, Denmark

**Matthias Bissinger né Kühnel**, ECAP, FAU Erlangen-Nürnberg, 96049 Bamberg, Germany

**Christian Malacaria**, National Space Science and Technology Center, Huntsville, AL 35805, USA

**Katja Pottschmidt**, University of Maryland Baltimore County, Baltimore, MD 21250, USA

**Richard E. Rothschild**, CASS, University of California San Diego, La Jolla, CA 92093, USA

**Rüdiger Staubert**, IAA, University of Tübingen, 72076 Tübingen, Germany

**John A. Tomsick**, University of California at Berkeley, Berkeley, CA 94720, USA

**Brent West**, Commander, Naval Surface Force, U.S. Pacific Fleet, San Diego, CA 92155, USA

**Jörn Wilms**, ECAP, FAU Erlangen-Nürnberg, 96049 Bamberg, Germany

**Colleen Wilson-Hodge**, NASA Marshall Space Flight Center, Huntsville, AL 35812, USA

**Abstract:** Studying the physical processes occurring in the region just above the magnetic poles of strongly magnetized, accreting binary neutron stars is essential to our understanding of stellar and binary system evolution. Perhaps more importantly, it provides us with a natural laboratory for studying the physics of high temperature and density plasmas exposed to extreme radiation, gravitational, and magnetic fields. Observations over the past decade have shed new light on the manner in which plasma falling at near the speed of light onto a neutron star surface is halted. Recent advances in modeling these processes have resulted in direct measurement of the magnetic fields and plasma properties. On the other hand, numerous physical processes have been identified that challenge our current picture of how the accretion process onto neutron stars works. Observation and theory are our essential tools in this regime because the extreme conditions cannot be duplicated on Earth. This white paper gives an overview of the current theory, the outstanding theoretical and observational challenges, and the importance of addressing them in contemporary astrophysics research.

# 1 Motivation

Neutron stars (NSs) occupy a unique position in the Universe. They are the only laboratories for the study of cold, ultradense matter, likely exceeding nuclear densities at their cores (see, e.g., Lattimer, 2012, for a review). They can harbor extremely strong magnetic fields, up to  $10^{15}$  G, representing the only place in the Universe where we can study such fields. And, as GW170817 (Abbott et al., 2017) proved, NS mergers are the primary source of heavy elements in the Universe. Hence, studying NS physics will remain a major research priority in the coming decade.

Neutron star physics can be ideally studied in accreting binary systems, where the NS accretes matter from its less-evolved companion. Systems with massive donors (“high-mass X-ray binaries” or HMXBs, with OB-star donors; Meszaros, 1992) are of special interest as possible NS-NS merger progenitors. The accretion by the NS is a key element to understanding the evolution of these systems. Furthermore, binary systems containing a NS and a Be-type companion are also of special interest, since these systems can display highly variable accretions rates onto the NS.

An accreting NS gravitationally captures matter from its companion, either via a stellar wind, Roche lobe overflow, or from the disk of a Be-type companion. This often forms an accretion disk around the NS, similar to what is seen in black hole (BH) binaries (e.g., Ghosh and Lamb, 1978; Shakura and Sunyaev, 1973). However, the NS’s extremely strong magnetic field disrupts the disk at the magnetospheric radius,  $R_m \sim 10^8$  cm, where the magnetic pressure begins to dominate over the ram pressure of the infalling material. The disk inner edge is thus significantly farther out than in a BH, and the fluid-like mixture of ionized gas, coupled with radiation, is channelled along the field lines into the top of the NS accretion column and the polar cap region, reaching free-fall velocities of  $\sim 0.5c$  with ion and electron temperatures up to  $10^7$ - $10^8$  K (see, e.g., Basko and Sunyaev, 1976; West et al., 2017a).

The disk properties, and the disk truncation distance, are mass transfer rate and NS magnetic field strength dependent. While there are a number of methods for estimating NS magnetic field strengths, many are indirect and rely on poorly-understood phenomena. However, accreting NSs provide one of the few *direct* measurements of the field strength: *cyclotron resonant scattering features* (CRSFs, or “cyclotron lines”). Additionally, as these features are produced by photons scattering on electrons in  $\sim 10^{12}$  G fields, they act as probes of the environment close to the NS surface. CRSFs make accreting NSs highly attractive targets for detailed studies of accretion. However, in order for this information to be useful, we must have a thorough knowledge of the physical processes involved, as well as a wide-ranging sample of data with which to test our understanding.

## 2 Physics of Emission from the Magnetic Poles of Neutron Stars

As ionized matter falls towards the surface of the star, soft X-ray photons generated in the flow are Compton upscattered in energy, cooling and braking the plasma while producing the observed hard

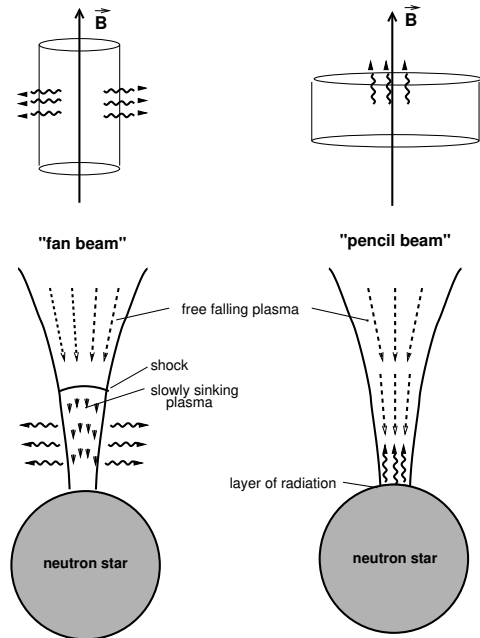


Figure 1: Left: “Fan-beam”/cylinder geometry. Right: “pencil beam”/slab geometry. From Schönherr et al. (2007).

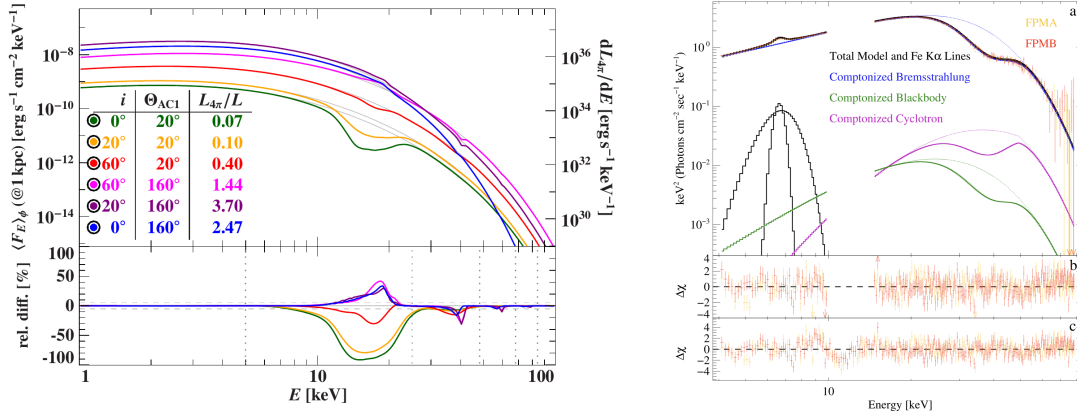


Figure 2: *Left*: Simulated observed spectra from a NS accretion column at different viewing angles, from S. Falkner et al. (submitted). *Right*: From Wolff et al. (2016), the observed *NuSTAR* spectrum of Her X-1 fitted with the radiation-dominated radiative shock model of Becker and Wolff (2007).

X-rays (Becker and Wolff, 2007; West et al., 2017a, and references therein). The observed spectrum typically resembles a power-law with energy at low energies, transitioning to an exponentially falling spectrum above 10–20 keV. Analytical and numerical treatments of this “Comptonization” process and the resulting X-ray spectra have been presented, (e.g., Becker and Wolff, 2007; Farinelli et al., 2012; Postnov et al., 2015; West et al., 2017b). The response of the flow to this cooling and braking, and to changes in the accretion rate,  $\dot{M}$ , was studied by Becker et al. (2012), who found that the behavior of the column is determined by two main factors: is the infalling material moving supersonically? And, does radiation pressure play a significant role in halting the flow? Figure 1, from Schönherr et al. (2007), displays two extremes of behavior: the left side shows the high  $\dot{M}$  case ( $\dot{M} \sim 10^{17} \text{ g s}^{-1}$ ), with supersonic flow, significant radiation pressure, and “fan-beam” emission from the sides of the column, while the right side shows the low  $\dot{M}$  case ( $\dot{M} \sim 10^{14} - 10^{15} \text{ g s}^{-1}$ ), where the infalling matter impacts directly on the NS surface and is halted by Coulomb collisions, producing a so-called “pencil-beam”, where the emission is directed mostly upwards, along the field lines.

## 2.1 Cyclotron Resonance Scattering Features – Measuring the Magnetic Field

In addition to the cut-off power-law X-ray spectrum described above, approximately three dozen of the  $\sim 350$  known accreting pulsars also display broad absorption-like features in the 10–100 keV range (Staubert et al., 2019). These *cyclotron resonance scattering features* are due to resonant scattering of photons on electrons in the strong magnetic field. The perpendicular motion of electrons relative to magnetic fields is quantized into Landau levels, the approximate spacing of which is given by  $\Delta E \approx 11.6 (\text{keV}) B_{12}$ , where  $B_{12}$  is the field strength in  $10^{12} \text{ G}$ . This results in a highly energy- and direction-dependent scattering cross-section, with resonances at (approximately) integer multiples of the energy spacing from  $\Delta E$ . NSs with field strengths of  $10^{12} - 10^{13} \text{ G}$  thus display these features in the 10–100 keV band, accessible to hard X-ray spectrometers (see Fig. 2, right). The observed features are broad ( $\Delta E/E \sim 0.1$ ), likely due to a combination of thermal motion and averaging over different angles to the magnetic field. The dependence on angle also means these features are intrinsically dependent on the pulse phase of the observed pulsar, reinforcing the need for missions with the time resolution and effective area to carry out pulse phase-resolved analyses.

Building on earlier work by Wang et al. (1988) and Araya and Harding (1996), we are now able to calculate self-consistent line profiles for cyclotron lines (Schönherr et al., 2007, 2014; Schwarm et al., 2017a,b), and by combining these results with new models for the X-ray continuum (see

Section 2.2 below) and gravitational light bending, we can produce realistic X-ray spectra and pulse profiles (Falkner et al., submitted, see Fig. 2). Comparing these models to observations is difficult, due to the computational expense and intrinsically large number of free parameters, but not impossible, and advances in computing power and analysis techniques (e.g., Markov Chain Monte Carlo analyses or machine learning approaches) will make this a significantly more feasible goal in the coming decade. This goal must be pursued if we want to further our understanding the extreme physical processes occurring in the NS environment, which cannot be duplicated on Earth.

## **2.2 Detailed Modeling of the Continuum from First Principles**

The extreme physics of the flow structure in the column makes modeling the continuum generated by accretion onto the magnetic poles of NSs very difficult. The radiation-dominated flow model (Arons et al., 1987; Davidson, 1973) has shown considerable promise in accounting for the radiation properties of luminous accreting X-ray pulsars such as Her X-1. We already know that unlike the Coulomb collisional stopping and collisionless shock models (e.g., Langer and Rappaport, 1982), radiation-dominated flow models can account for the general shape of the X-ray spectra at X-ray luminosities near and above the “critical luminosity” (Wolff et al., 2016, see Fig. 2). The theoretical spectra display exponential Compton cut-offs in the high energy X-ray range (10–40 keV) just like those observed, and power-law continua that can be understood as Compton upscattering of the high energy photon distributions in the plasma. This theoretical spectrum shows agreement with the observed spectrum over nearly 2 orders of magnitude in energy.

A critical assumption in the emerging theoretical development, and one that is almost certainly incorrect, is that one type of flow model, namely a radiation-dominated shock where electron scattering is completely efficient in stopping the plasma flow near the NS surface, is applicable in all sources, from the low luminosity steep-spectrum sources such as X Persei, to the high luminosity flat spectrum sources such as LMC X-4 and Cen X-3. But how do accretion flows onto NSs transition from gas-dominated to radiation-dominated? This is not known. Perhaps as the luminosity decreases, gas-mediated, thermal “sub-shocks” develop in the radiation-dominated flows in a manner suggested by (Becker and Kazanas, 2001) in their study of cosmic-ray acceleration in super-driven shock waves. Another critical question for our understanding of the accretion flow structures is whether the emergent radiation comes out in a fan beam, in a pencil beam, or both?

Another aspect of the problem is the energy budget. This involves the details of the production of the cyclotron, bremsstrahlung, and blackbody “seed photons,” and how these photons interact with the gas to heat or cool the plasma, extract energy from the accretion column, and form the broad continuum spectrum. In principle, the dynamics and the spectral formation must be treated self-consistently, which is an extremely difficult “grand challenge” level simulation. Initial steps in this direction have been accomplished by West et al. (2017a,b), but these calculations were limited to one spatial direction (radial), and are not time-dependent. In a fully self-consistent model, the radiation regulates the structure of the flows as it merges with the NS atmosphere.

## **3 Recent Observational Advances and Goals for the Coming Decade**

### **3.1 The CRSF Energy-Luminosity Relationship**

The first source with a clear correlation between the CRSF energy and the X-ray luminosity was Her X-1 (Staubert et al., 2007). Since then, measurements of the energy-luminosity relationship have been made for several other X-ray pulsars, thanks in large part to the capabilities of *NuSTAR*. As shown in the left panel of Fig. 3, the CRSF energy-luminosity relation is bimodal with source luminosity (Becker et al., 2012). The two sources with negative CRSF energy-luminosity

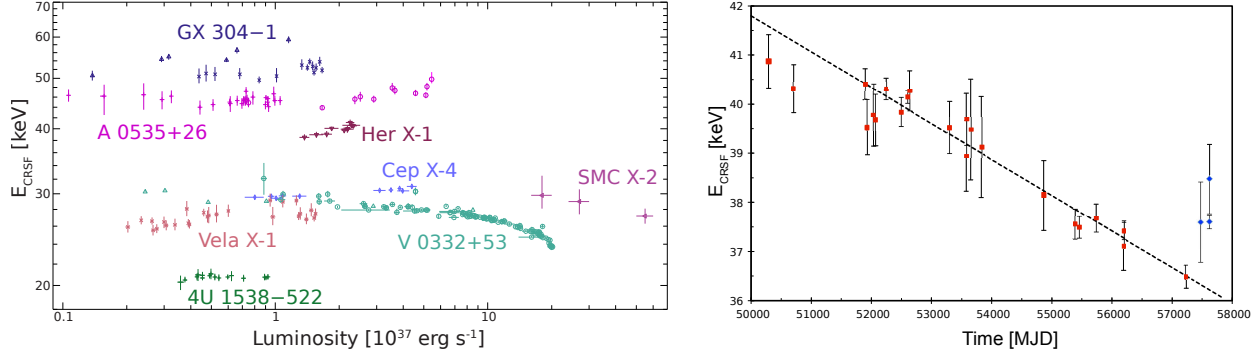


Figure 3: Left: CRSF energy vs. luminosity for a number of sources, adapted from Staubert et al. (2019). Right: Her X-1’s long-term decay in CRSF energy, adapted from Staubert et al. (2017).

relations, V 0332+53 (Tsygankov et al., 2006) and SMC X-2 (Jaisawal and Naik, 2016), are the brightest known CRSF sources, while Her X-1 and the other sources displaying positive correlations (e.g., Vela X-1 Fürst et al., 2014) are lower-luminosity. Others at still lower luminosity (e.g., 4U 1538–522 Hemphill et al., 2016) show no evolution of CRSF energy with luminosity. Different theoretical models have been put forward to explain these dependencies — e.g. the shock-height model of Becker et al. (2012), or the reflection-model of Postnov et al. (2015). However, a full explanation is lacking, and is hampered by the small number of sources with good enough data to observe a trend, particularly at low luminosities. Future observations made with detectors with enhanced spectral and temporal resolution, combined with new theoretical work, are necessary to understand this aspect of accretion onto the magnetic poles of NSs.

### 3.2 Evolution of the Continuum Shape with Luminosity

The observed spectra of many accreting NSs seem to harden with increasing luminosity (see, e.g., Reig and Nespoli, 2013). This behavior can be explained by an increase in the “bulk Comptonization” process (Postnov et al., 2015), which transfers bulk kinetic energy from the inflowing gas directly to the emergent hard X-ray spectra. The typical luminosities associated with this type of spectral hardening are on the order of  $10^{36} - 10^{37} \text{ erg s}^{-1}$ . There is growing evidence from detailed spectral analyses of large amounts of observations that at higher luminosities the hardening saturates or even starts to decrease again (see, e.g., Kühnel et al., 2017; Postnov et al., 2015; Reig and Milonaki, 2016). This has been interpreted as a transition from the Coulomb-dominated accretion regime to the radiation-dominated one. At luminosities way below  $10^{36} \text{ erg s}^{-1}$  very soft spectra have been observed, which might indicate a transition to a regime where the physical mechanism capable of stopping the infalling material is yet to be explored (Kühnel et al., 2017; Tsygankov et al., 2019).

### 3.3 A New Development: Long-Term Variation of the Cyclotron Line

A major discovery of the past decade was the measurement by Staubert et al. (2014) of an upwards jump followed by a significant secular decay ( $\sim 0.3 \text{ keV yr}^{-1}$ ) in the CRSF energy of Her X-1, unrelated to the source luminosity (see Fig. 3, right). Since then, similar trends have been detected in three more sources: Vela X-1 (long-term decay, see Ji et al., 2019; La Parola et al., 2016), V 0332+53 (short- and long-term changes, see Vybornov et al., 2018), and 4U 1538–522 (upwards jump, see Hemphill et al., 2016; Hemphill et al., 2019). The physical mechanism behind this is unknown, but must be related to some restructuring of the accretion flow near the polar regions of the NS — e.g., accumulations of accreted plasma could distort the field, or the accreted material could collapse or leak out of the magnetically-confined mound on the surface. This reinforces the

Table 1: Requirements for future X-ray missions

Parameter	Requirement	Scientific Justification
Energy bandpass	10–100 keV 0.5–10 keV	Known CRSF band Continuum & absorption constraint
Energy resolution	$\Delta E/E \lesssim 1$ keV @ 30 keV	Detailed CRSF profiles
Time resolution	$\lesssim 100 \mu\text{s}$	Phase-connected, -resolved spectroscopy
Sensitivity	$10^{-12}$ erg cm <sup>-2</sup> s <sup>-1</sup>	Low- $\dot{M}$ and quiescent sources
Photon pile-up	$\lesssim 10\%$ @ 5 Crab	Bright sources in outburst
Observing flexibility	~1-day repoint	Rapid response to X-ray transients
Polarization	MDP $\lesssim 20\%$ @ 30 keV	Detect polarization in CRSF band
All-sky monitoring	$10^{-10}$ erg cm <sup>-2</sup> s <sup>-1</sup>	Long-timescale variability

need for detailed theoretical and simulation-based treatments of NS accretion.

### 3.4 Going to Extremes: the Brightest Neutron Stars in the Sky

With the recent discovery of ultra-luminous X-ray pulsars (ULXPs), it has been proven that NSs can reach isotropic luminosities up to at least  $10^{41}$  erg s<sup>-1</sup> (Bachetti et al., 2014; Israel et al., 2017). Most ULXPs are extragalactic sources, and their large distances make detailed studies with existing instruments difficult. However, even within the Milky Way and the Magellanic Clouds, we have a few examples of NSs breaching their Eddington limit, albeit by a less extreme factor. The transient Swift J0243.6+612 recently underwent an extremely bright outburst, likely reaching over  $10^{39}$  erg s<sup>-1</sup> at its peak (Wilson-Hodge et al., 2018). The source’s pulse profile evolved dramatically over the outburst, suggesting a changing emission geometry due to transitions between accretion regimes. Detailed studies of such transitions are key to understanding the physics involved. Another example is LMC X-4, in which, as discovered by Brumback et al. (2018), pulsations sometimes disappear without obvious changes in flux, similar to the ULXP M82 X-2 (Karino and Miller, 2016). The reasons for these changes are still unclear. To advance our understanding of this behavior, dedicated monitoring by instruments with high time resolution, and good spectral and angular resolution, is necessary. Additionally, ULXPs’ apparent super-Eddington accretion rates reinforce the need, as laid out in Section 2, for a solid theoretical understanding of the emission geometry and the spectral formation mechanism operative in such systems.

## 4 Requirements on Future X-ray Missions

The topics laid out above allow us to form a fairly clear picture of how X-ray missions need to evolve in order to achieve our goals. Of prime importance is broad-band coverage with good energy resolution, as will be provided by missions like *HEX-P* (Madsen et al., 2017), which is necessary to detect CRSFs and constrain their profiles. All-sky or wide-field monitoring, flexible scheduling, and fast response times, with a mission such as *STROBE-X* (Ray et al., 2019), will be essential for responding to sources in outburst. We must also be able to track sources to very high and very low luminosities in order to probe the full range of accretion regimes. Finally, CRSFs are a prime target for X-ray polarimetry studies, since large variations in polarization fraction and angle are expected over the pulse (see, e.g. Vadawale et al., 2018, for the case of the Crab pulsar), especially in the vicinity of the CRSF energy. With the coming launch of *IXPE*, X-ray polarimetry at softer X-ray energies will become a reality, but there is an urgent need for an instrument with polarimetry capabilities in the 10–100 keV band. We summarize these mission requirements in Table 1.

## 5 References

- B. P. Abbott, R. Abbott, T. D. Abbott, F. Acernese, K. Ackley, C. Adams, T. Adams, P. Addesso, R. X. Adhikari, V. B. Adya, and et al. Multi-messenger Observations of a Binary Neutron Star Merger. *ApJ*, 848:L12, Oct. 2017. doi: 10.3847/2041-8213/aa91c9.
- R. A. Araya and A. K. Harding. Cyclotron line models for the X-ray pulsar A 0535+26. *Astronomy and Astrophysics Supplement Series*, 120, Nov. 1996.
- J. Arons, R. I. Klein, and S. M. Lea. Radiation gasdynamics of polar CAP accretion onto magnetized neutron stars - Basic theory. *The Astrophysical Journal*, 312:666–699, Jan. 1987. ISSN 0004-637X. doi: 10.1086/164912.
- M. Bachetti, F. A. Harrison, D. J. Walton, B. W. Grefenstette, D. Chakrabarty, F. Fürst, D. Barret, A. Beloborodov, S. E. Boggs, F. E. Christensen, W. W. Craig, A. C. Fabian, C. J. Hailley, A. Hornschemeier, V. Kaspi, S. R. Kulkarni, T. Maccarone, J. M. Miller, V. Rana, D. Stern, S. P. Tendulkar, J. Tomsick, N. A. Webb, and W. W. Zhang. An ultraluminous X-ray source powered by an accreting neutron star. *Nature*, 514:202–204, Oct. 2014. doi: 10.1038/nature13791.
- M. M. Basko and R. A. Sunyaev. The Limiting Luminosity of Accreting Neutron Stars With Magnetic Fields. *Monthly Notices of the Royal Astronomical Society*, 175(2):395–417, Jan. 1976. ISSN 0035-8711, 1365-2966. doi: 10.1093/mnras/175.2.395.
- P. A. Becker and D. Kazanas. Exact Expressions for the Critical Mach Numbers in the Two-Fluid Model of Cosmic-Ray-modified Shocks. *The Astrophysical Journal*, 546:429–446, Jan. 2001. ISSN 0004-637X. doi: 10.1086/318257.
- P. A. Becker and M. T. Wolff. Thermal and Bulk Comptonization in Accretion-powered X-Ray Pulsars. *The Astrophysical Journal*, 654(1): 435, 2007. doi: 10.1086/509108.
- P. A. Becker, D. Klochkov, G. Schönherr, O. Nishimura, C. Ferrigno, I. Caballero, P. Kretschmar, M. T. Wolff, J. Wilms, and R. Staubert. Spectral formation in accreting X-ray pulsars: Bimodal variation of the cyclotron energy with luminosity. *Astronomy and Astrophysics*, 544:A123, Aug. 2012. ISSN 0004-6361. doi: 10.1051/0004-6361/201219065.
- M. C. Brumback, R. C. Hickox, M. Bachetti, R. Ballhausen, F. S. Fürst, S. Pike, K. Pottschmidt, J. A. Tomsick, and J. Wilms. Discovery of Pulsation Dropout and Turn-on during the High State of the Accreting X-Ray Pulsar LMC X-4. *ApJ*, 861:L7, July 2018. doi: 10.3847/2041-8213/aacd13.
- K. Davidson. Accretion at a Magnetic Pole of a Neutron Star. *Nature Physical Science*, 246 (149):1–4, Nov. 1973. ISSN 0300-8746. doi: 10.1038/physci246001a0.
- R. Farinelli, C. Ceccobello, P. Romano, and L. Titarchuk. Numerical solution of the radiative transfer equation: X-ray spectral formation from cylindrical accretion onto a magnetized neutron star. *Astronomy and Astrophysics*, 538:A67, Feb. 2012. ISSN 0004-6361. doi: 10.1051/0004-6361/201118008.
- F. Fürst, K. Pottschmidt, J. Wilms, J. A. Tomsick, M. Bachetti, S. E. Boggs, F. E. Christensen, W. W. Craig, B. W. Grefenstette, C. J. Hailley, F. Harrison, K. K. Madsen, J. M. Miller, D. Stern, D. J. Walton, and W. Zhang. NuSTAR Discovery of a Luminosity Dependent Cyclotron Line Energy in Vela X-1. *The Astrophysical Journal*, 780(2):133, 2014. ISSN 0004-637X. doi: 10.1088/0004-637X/780/2/133.
- P. Ghosh and F. K. Lamb. Disk accretion by magnetic neutron stars. *The Astrophysical Journal*, 223:L83, July 1978. doi: 10.1086/182734.
- P. B. Hemphill, R. E. Rothschild, F. Fürst, V. Grinberg, D. Klochkov, P. Kretschmar, K. Pottschmidt, R. Staubert, and J. Wilms. Evidence for an evolving cyclotron line energy in 4U 1538-522. *Monthly Notices of the Royal Astronomical Society*, 458(3):2745, 2016. doi:

- 10.1093/mnras/stw470.
- P. B. Hemphill, R. E. Rothschild, D. M. Cheatham, F. Fürst, P. Kretschmar, M. Kühnel, K. Pottschmidt, R. Staubert, J. Wilms, and M. T. Wolff. The First NuSTAR Observation of 4U 1538-522: Updated Orbital Ephemeris and A Strengthened Case for an Evolving Cyclotron Line Energy. *arXiv e-prints*, art. arXiv:1901.11071, Jan 2019.
- G. L. Israel, A. Belfiore, L. Stella, P. Esposito, P. Casella, A. De Luca, M. Marelli, A. Papitto, M. Perri, S. Puccetti, G. A. R. Castillo, D. Salvetti, A. Tiengo, L. Zampieri, D. D’Agostino, J. Greiner, F. Haberl, G. Novara, R. Salvaterra, R. Turolla, M. Watson, J. Wilms, and A. Wolter. An accreting pulsar with extreme properties drives an ultraluminous x-ray source in NGC 5907. *Science*, 355:817–819, Feb. 2017. doi: 10.1126/science.aai8635.
- G. K. Jaisawal and S. Naik. Detection of cyclotron resonance scattering feature in high-mass X-ray binary pulsar SMC X-2. *MNRAS*, 461:L97–L101, Sept. 2016. doi: 10.1093/mnras/slw108.
- L. Ji, R. Staubert, L. Ducci, A. Santangelo, S. Zhang, and Z. Chang. Long-term evolutions of the cyclotron line energies in Her X-1, Vela X-1, and Cen X-3 as observed with Swift/BAT. *MNRAS*, 484:3797–3805, Apr. 2019. doi: 10.1093/mnras/stz264.
- S. Karino and J. C. Miller. Accretion mode of the ultraluminous X-ray source M82 X-2. *MNRAS*, 462:3476–3482, Nov. 2016. doi: 10.1093/mnras/stw1180.
- M. Kühnel, F. Fürst, K. Pottschmidt, I. Kreykenbohm, R. Ballhausen, S. Falkner, R. E. Rothschild, D. Klochkov, and J. Wilms. Evidence for different accretion regimes in gro j1008-57. *Astronomy & Astrophysics*, 607:A88, Nov. 2017.
- V. La Parola, G. Cusumano, A. Segreto, and A. D’Ai. The Swift-BAT monitoring reveals a long-term decay of the cyclotron line energy in Vela X-1. *MNRAS*, 463:185–190, Nov 2016. doi: 10.1093/mnras/stw1915.
- S. H. Langer and S. Rappaport. Low-luminosity accretion onto magnetized neutron stars. *The Astrophysical Journal*, 257:733, June 1982. ISSN 0004-637X, 1538-4357. doi: 10.1086/160028.
- J. M. Lattimer. The nuclear equation of state and neutron star masses. *Annual Review of Nuclear and Particle Science*, 62:485–515, Nov. 2012.
- K. Madsen, F. Harrison, D. Stern, B. Grefenstette, V. Rana, and H. Miyasaka. The High-Energy X-ray Probe (HEX-P). In *AAS/High Energy Astrophysics Division #16*, volume 16 of *AAS/High Energy Astrophysics Division*, page 103.21, Aug. 2017.
- P. Meszaros. *High-energy radiation from magnetized neutron stars*. University of Chicago Press, 1992.
- K. A. Postnov, M. I. Gornostaev, D. Klochkov, E. Laplace, V. V. Lukin, and N. I. Shakura. On the dependence of the X-ray continuum variations with luminosity in accreting X-ray pulsars. *Monthly Notices of the Royal Astronomical Society*, 452:1601–1611, Sept. 2015. ISSN 0035-8711. doi: 10.1093/mnras/stv1393.
- P. S. Ray, Z. Arzoumanian, D. Ballantyne, E. Bozzo, S. Brandt, L. Brennerman, D. Chakrabarty, M. Christophersen, A. r. DeRosa, M. Feroci, K. Gendreau, A. Goldstein, D. Hartmann, M. Hernanz, P. Jenke, E. Kara, T. Maccarone, M. McDonald, M. Nowak, B. Phlips, R. Remillard, A. Stevens, J. Tomsick, A. Watts, C. Wilson-Hodge, K. Wood, and S. Zane. STROBE-X: X-ray Timing and Spectroscopy on Dynamical Timescales from Microseconds to Years. *arXiv e-prints*, art. arXiv:1903.03035, Mar 2019.
- P. Reig and F. Milonaki. Accretion regimes in the X-ray pulsar 4U 1901+03. *Astronomy & Astrophysics*, 594:A45, Oct. 2016.
- P. Reig and E. Nespoli. Patterns of variability in be/x-ray pulsars during giant outbursts. *Astronomy & Astrophysics*, 551, Mar. 2013.
- G. Schönherr, J. Wilms, P. Kretschmar, I. Kreykenbohm, A. Santangelo, R. E. Roth-



- schild, W. Coburn, and R. Staubert. A model for cyclotron resonance scattering features. *Astronomy and Astrophysics*, 472:353–365, Sept. 2007. ISSN 0004-6361. doi: 10.1051/0004-6361:20077218.
- G. Schönherr, F.-W. Schwarm, S. Falkner, T. Dauser, C. Ferrigno, M. Kühnel, D. Klochkov, P. Kretschmar, P. A. Becker, M. T. Wolff, K. Pottschmidt, M. Falanga, I. Kreykenbohm, F. Fürst, R. Staubert, and J. Wilms. Formation of phase lags at the cyclotron energies in the pulse profiles of magnetized, accreting neutron stars. *Astronomy & Astrophysics*, 564:L8, Apr. 2014. ISSN 0004-6361, 1432-0746. doi: 10.1051/0004-6361/201322448.
- F.-W. Schwarm, R. Ballhausen, S. Falkner, G. Schönherr, K. Pottschmidt, M. T. Wolff, P. A. Becker, F. Fürst, D. M. Marcu-Cheatham, P. B. Hemphill, E. Sokolova-Lapa, T. Dauser, D. Klochkov, C. Ferrigno, and J. Wilms. Cyclotron resonant scattering feature simulations. II. Description of the CRSF simulation process. *Astronomy and Astrophysics*, 601:A99, May 2017a. doi: 10.1051/0004-6361/201630250.
- F.-W. Schwarm, G. Schönherr, S. Falkner, K. Pottschmidt, M. T. Wolff, P. A. Becker, E. Sokolova-Lapa, D. Klochkov, C. Ferrigno, F. Fürst, P. B. Hemphill, D. M. Marcu-Cheatham, T. Dauser, and J. Wilms. Cyclotron resonant scattering feature simulations. I. Thermally averaged cyclotron scattering cross sections, mean free photon-path tables, and electron momentum sampling. *Astronomy and Astrophysics*, 597:A3, Jan. 2017b. doi: 10.1051/0004-6361/201629352.
- N. I. Shakura and R. A. Sunyaev. Black holes in binary systems. Observational appearance. *Astronomy and Astrophysics*, 24, 1973.
- R. Staubert, N. I. Shakura, K. Postnov, J. Wilms, R. E. Rothschild, W. Coburn, L. Rodina, and D. Klochkov. Discovery of a flux-related change of the cyclotron line energy in Hercules X-1. *Astronomy and Astrophysics*, 465:L25–L28, Apr. 2007. ISSN 0004-6361. doi: 10.1051/0004-6361:20077098.
- R. Staubert, D. Klochkov, J. Wilms, K. Postnov, N. I. Shakura, R. E. Rothschild, F. Fürst, and F. A. Harrison. Long-term change in the cyclotron line energy in Hercules X-1. *Astronomy and Astrophysics*, 572:A119, Dec. 2014. ISSN 0004-6361. doi: 10.1051/0004-6361/201424203.
- R. Staubert, D. Klochkov, F. Fürst, J. Wilms, R. E. Rothschild, and F. Harrison. Inversion of the decay of the cyclotron line energy in Hercules X-1. *Astronomy and Astrophysics*, 606:L13, Oct. 2017. doi: 10.1051/0004-6361/201731927.
- R. Staubert, J. Trümper, E. Kendziorra, D. Klochkov, K. Postnov, P. Kretschmar, K. Pottschmidt, F. Haberl, R. E. Rothschild, A. Santangelo, J. Wilms, I. Kreykenbohm, and F. Fürst. Cyclotron lines in highly magnetized neutron stars. *Astronomy & Astrophysics*, 622:A61, Jan. 2019. doi: 10.1051/0004-6361/201834479.
- S. S. Tsygankov, A. A. Lutovinov, E. M. Churazov, and R. A. Sunyaev. V0332+53 in the outburst of 2004–2005: Luminosity dependence of the cyclotron line and pulse profile. *Monthly Notices of the Royal Astronomical Society*, 371(1):19, Sept. 2006. doi: 10.1111/j.1365-2966.2006.10610.x.
- S. S. Tsygankov, A. Rouco Escorial, V. F. Suleimanov, A. A. Mushtukov, V. Doroshenko, A. A. Lutovinov, R. Wijnands, and J. Poutanen. Dramatic spectral transition of x-ray pulsar gx 304-1 in low luminous state. *Monthly Notices of the Royal Astronomical Society*, 483:L144–L148, Feb. 2019.
- S. V. Vadawale, T. Chattopadhyay, N. P. S. Mithun, A. R. Rao, D. Bhattacharya, A. Vibhute, V. B. Bhalerao, G. C. Dewangan, R. Misra, B. Paul, A. Basu, B. C. Joshi, S. Sreekumar, E. Samuel, P. Priya, P. Vinod, and S. Seetha. Phase-resolved X-ray polarimetry of the Crab pulsar with the AstroSat CZT Imager. *Nature Astronomy*, 2:50–55, Nov 2018. doi: 10.1038/s41550-017-0293-z.

- V. Vybornov, V. Doroshenko, R. Staubert, and A. Santangelo. Changes in the cyclotron line energy on short and long timescales in V 0332+53. *Astronomy and Astrophysics*, 610:A88, Mar. 2018. ISSN 0004-6361. doi: 10.1051/0004-6361/201731750.
- J. C. L. Wang, I. M. Wasserman, and E. E. Salpeter. Cyclotron line resonant transfer through neutron star atmospheres. *The Astrophysical Journal Supplement Series*, 68: 735–802, Dec. 1988. ISSN 0067-0049. doi: 10.1086/191303.
- B. F. West, K. D. Wolfram, and P. A. Becker. A New Two-fluid Radiation-hydrodynamical Model for X-Ray Pulsar Accretion Columns. *The Astrophysical Journal*, 835(2):129, Feb. 2017a. doi: 10.3847/1538-4357/835/2/129.
- B. F. West, K. D. Wolfram, and P. A. Becker. Dynamical and Radiative Properties of X-Ray Pulsar Accretion Columns: Phase-averaged Spectra. *The Astrophysical Journal*, 835(2): 130, Feb. 2017b. doi: 10.3847/1538-4357/835/2/130.
- C. A. Wilson-Hodge, C. Malacaria, P. A. Jenke, G. K. Jaisawal, M. Kerr, M. T. Wolff, Z. Arzoumanian, D. Chakrabarty, J. P. Doty, K. C. Gendreau, S. Guillot, W. C. G. Ho, B. LaMarr, C. B. Markwardt, F. Özel, G. Y. Prigozhin, P. S. Ray, M. Ramos-Lerate, R. A. Remillard, T. E. Strohmayer, M. L. Vezie, K. S. Wood, and NICER Science Team. NICER and Fermi GBM Observations of the First Galactic Ultra-luminous X-Ray Pulsar Swift J0243.6+6124. *The Astrophysical Journal*, 863:9, Aug. 2018. doi: 10.3847/1538-4357/aace60.
- M. T. Wolff, P. A. Becker, A. M. Gottlieb, F. Fürst, P. B. Hemphill, D. M. Marcu-Cheatham, K. Pottschmidt, F.-W. Schwarm, J. Wilms, and K. S. Wood. The NuSTAR X-Ray Spectrum of Hercules X-1: A Radiation-dominated Radiative Shock. *The Astrophysical Journal*, 831(2):194, Nov. 2016. doi: 10.3847/0004-637X/831/2/194.