Decadal Review White Paper

Physics of the Accretion Mound at the Magnetic Poles of Neutron Stars

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Summary: The study of the physical processes in the region just above the magnetic poles of strongly magnetic accreting neutron stars is essential to the understanding of stellar and binary system evolution, as well as that of the origin and evolution of neutron star magnetic fields. Recent advances in modeling these processes have resulted in direct measurement of the magnetic fields and plasma parameters in physical units as opposed to empirical ones.

Motivation: Understanding the behavior of matter under extreme physical conditions is one of the outstanding themes in high energy astrophysics investigations. The atmospheres at the magnetic poles of compact, rapidly rotating neutron stars accreting material from a stellar companion provide extremes of temperature, density, gravity, and magnetic field unobtainable in the terrestrial environment.

Neutron stars are the compact remnants of the stellar evolution of stars with masses $\gtrsim 8\,M_\odot$, where $M_\odot$ is the mass of our Sun. With masses of $\sim 1.4\,M_\odot$, radii of ~ 10 km, only slightly above their Schwarzschild radius, and corresponding densities comparable to the nuclear density, $\rho \gtrsim 10^{14}\,\mathrm{g\,cm^{-3}}$, they are the most compact "normal" objects in the universe.

The origin of the magnetic field of neutron stars is one of the big mysteries of modern astrophysics. As summarized, e.g., by Reisenegger (2003), current theories posit that the magnetic fields are the remnant of the magnetic field of the progenitor star, which was created by a dynamo process in the center of the star. Conservation of magnetic flux, $\Phi_B \propto BR^2$, during the core collapse of the progenitor then amplifies the magnetic field, resulting in estimated neutron star magnetic fields on the order of 10^{11}–10^{15} G.

Magnetic fields are of fundamental importance for the behavior and evolution of neutron stars in X-ray binary systems. In these systems, matter from a normal star accretes onto the neutron star. Due to its angular momentum, a disk forms in which the material falls on quasi-Keplerian orbits towards the neutron star, getting heated up to temperatures such that the peak of the emission is in the UV and soft X-ray bands (Shakura, 1973). The behavior at the inner edge of this accretion disk depends on the neutron star's magnetic field:

1. If the neutron star has a strong magnetic field, the accreted plasma couples onto the magnetic field at a significant distance away from the neutron star (several 100 neutron star radii) and then falls along the B-

field lines onto the magnetic poles of the neutron star, where it is heated up to temperatures $kT \gtrsim 1\,\mathrm{keV}$ and thus becomes observable in the X-rays. As the neutron star rotates, these hot spots pass through our line of sight, resulting in a periodic X-ray signal. These systems are called X-ray pulsars, they are typically found in systems where the donor star is a young O- or B-star. These systems are also called High Mass X-ray Binaries (HMXBs).

2. On systems where the donor is of low mass, Low Mass X-ray Binaries (LMXBs), persistent pulsations are not observed and the accretion disk extends deep into the gravitational potential well of the neutron star, where thermal X-ray emission is produced. This observation suggests that the magnetic field of neutron stars in LMXBs is considerably weaker than that in HMXBs.

As inferred from radio pulsar spin history measurements, older systems generally have smaller *B*-fields than young ones. In the context of neutron star evolutionary models, the observational difference in inferred neutron star magnetic field strengths between HMXBs and LMXBs is seen as an indication that the old neutron stars in LMXB systems have low magnetic fields, while the young neutron stars in HMXBs have strong magnetic fields. Similar results are also found for radio pulsars. Such observational results have led theoreticians to propose models in which diffusive processes within the neutron star lead to the magnetic field decay.

The evolutionary history of neutron star magnetic fields is thus responsible for their observational appearance, and therefore the knowledge of the neutron star *B*-fields is required to understand this whole class of objects. Most methods to determine neutron star magnetic fields are indirect and rely on rather poorly understood physical processes. This fact poses one of the major challenges in making further progress in understanding neutron stars (Reisenegger, 2003).

There is one method, however, which allows, in principle, for a direct measurement of the magnetic field. The motion of electrons around the magnetic field lines becomes quantized into so-called Landau levels. Photons passing through the accretion column, where most of the observed X-rays are produced, can interact with these quantized electrons through resonant Compton scatterings. If the photon energy corresponds to the energy difference between two Landau levels, the photon can inelastically scatter off the electron, leaving the electron in a higher Landau level. As a consequence of this resonant scattering, absorption-like lines can be observed at energies correspoding to the difference in energy between Landau levels. Specifically, the line energy is given by $E_n = n \cdot 12\,\mathrm{keV} \cdot B_{12}$, where n is an integer and where $B_{12} = B/10^{12}\,\mathrm{G}$. *Observations of these cyclotron lines thus provide a* direct *measurement of the neutron star magnetic fields.*

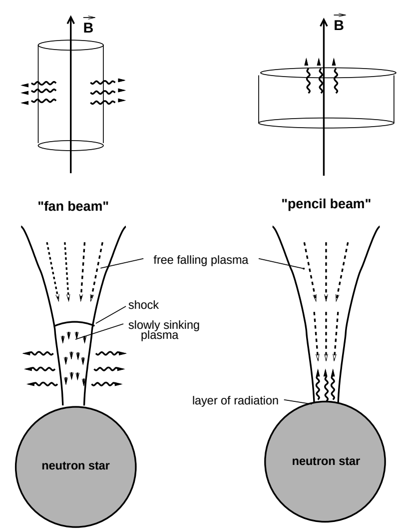

Figure 1: Accretion geometries and radiation patterns, *Left*: "fan beam"/cylinder geometry. *Right*: "pencil beam"/slab geometry. From Schönherr et al. (2007)

The Physics of Emission from the Magnetic Poles of Neutron Stars: As outlined above, neutron stars in binary systems accrete matter from a strong stellar wind, by contact with a Be star disk, or by Roche lobe overflow, usually through an accretion disk (Ghosh & Lamb, 1978). The magnetic field of the neutron star disrupts the flow of matter at the Alfvén radius, where the magnetic field pressure equals the ram pressure of the flow, and the matter is funneled along the field lines onto the magnetic poles (Basko & Sunyaev, 1976), reaching free-fall velocities of ~0.4c. In the field-dominated region near the neutron star surface, inverse Comptonization of soft photons in the decelerated plasma produces photons in the X-ray and gamma ray regime. The emission characteristics of this radiation depend on the mass accretion rate, $\dot{M}$. For large $\dot{M}$, a shock front develops at some distance from the neutron star surface, which does not permit the up-scattrered photons to escape vertically from the accretion column, i.e., parallel to the magnetic field. As a result, a "fan beam" emission pattern forms (Fig 1). As was first shown by Basko & Sunyaev (1976), the critical luminosity for shock formation, L^*, is

$$L^\star = 2.72 \cdot 10^{37} \left(\frac{\sigma_T}{\sqrt{\sigma_\parallel \sigma_\perp}}\right)\left(\frac{r_0}{R}\right)\left(\frac{M}{M_\odot}\right) \text{erg s}^{-1} \tag{1}$$

where r_0 is the polar cap radius, σ_T is the Thomson scattering cross section, $\sigma_\parallel$ and $\sigma_\perp$ are the energy averaged cross sections for the scattering of photons which propagate in parallel and perpendicular directions to the magnetic field direction (Becker, 1998). For small $\dot{M}$, on the other hand, i.e., for $L<L^*$, the radiation is emitted from a relatively compact accretion mound such that most photons are emitted parallel to the magnetic field in a "pencil beam" pattern (Fig 1).

Cyclotron Resonance Scattering Features – Measuring the Magnetic Field: Before emerging from the plasma, the high-energy photons undergo scattering processes with the electrons in the relativistic plasma of the accretion column. The scattering cross section is resonant at energies determined by the separation of the Landau energies, the discrete energy levels of the electrons. When the strength of the magnetic field B approaches the critical field strength, $B_{crit}=(m^2c^3)/(e\hbar)=4.4\times10^{13}$G, the de Broglie radius of a plasma electron becomes comparable to its Larmor radius. Quantum mechanical treatment of the electrons' motion perpendicular to the magnetic field lines (Lodenquai et al., 1974; Mészáros, 1992; Daugherty & Harding, 1986) reveals a quantization of the electrons' momenta $p_\perp/(m_e c)=n(B/B_{crit})$. This translates into discrete energy levels, where the fundamantal Landau level is given by $E_{cyc} \approx 11.57\,\text{keV} \times B_{12}$, and the higher harmonics have n times this energy. For photon-electron scattering, relativistic effects lead to a slightly anharmonic spacing of the resonant photon energies. Due to the large scattering cross section at the resonances and due to the quasi-harmonic spacing of the thermally broadened Landau levels, photons of energies close to the Landau level energies may not escape the line-forming region unless inelastic scattering has slightly changed their energy. Consequently, absorption-like features in the photon spectrum are observed at

$$E_n = m_e c^2 \frac{\sqrt{1+2n(B/B_\text{crit})\sin^2\theta}-1}{\sin^2\theta}\frac{1}{1+z} \approx \frac{2nE_{cyc}}{1+z}\left(1+\sqrt{1+2n\frac{E_{cyc}}{m_e c^2} sin^2\theta}\right)^{-1} \tag{2}$$

where m_e is the electron rest mass, c is the speed of light, θ the angle between the photon direction and the magnetic field vector, and z is the gravitational redshift at the radius of the line-forming region. One then enumerates the cyclotron resonance scattering features(CRSFs) or "cyclotron lines" starting at $n = 1$, and refers to them as the first or fundamental line at the energy $E_{cyc}=E_1$, followed by the second, third, etc. harmonics (n=2,3,...). The gravitational redshift at the neutron star surface is approximately[1]

$$z = \frac{1}{\sqrt{1-\frac{2GM}{Rc^2}}} - 1 \tag{3}$$

which gives $z\sim0.3$ assuming the typical neutron star parameters. The thermal motion of the electrons parallel to the magnetic field lines remains free and is characterized by the parallel electron temperature, T_e. Thus, the measured centroid energy of the fundamental yields a direct measure of the neutron star magnetic field.

Detailed Modeling of Cyclotron Resonance Scattering Features: Different approaches to modeling the radiative transfer in the accretion column have been attempted. One is solving finite difference equations, another is Monte Carlo simulations and a third involves a radiation-dominated shock. The first has been employed by Nagel (1980,1981) and later by Mészáros & Nagel (1985) and Nishimura (2003,2005). The

[1] Strictly speaking, Eq(3) is exact only for a non-rotating, spherically symmetric, uncharged mass.

second was initially used by Yahel (1979) and Wang et al. (1989), and most recently by Schönherr et al. (2007), who based their Monte Carlos on the pioneering work of Araya & Harding (1996,1999,2000). The third, due to Becker & Wolff (2007), is discussed below in the section on the continuum emission.

Instead of past empirical fitting using Gaussian or Lorentzian line shapes for the cyclotron lines and various continua recipes (e.g., power law with cutoff to exponential form beyond E_{cut}), new modeling of the CRSF alone by (Schönherr et al., 2007) has produced Green's functions suitable for detailed investigations of the physics in the accretion column via spectral fitting (XSPEC model cyclomc). Becker & Wolff (2007) have approached the problem by modeling the continuum and CRSF (see below). These have resulted in estimates of pertinent physical parameters involved.

Of the 16 accreting pulsars showing CRSFs in their X-ray spectra, multiple harmonics are detected in ~25%, with V0332+53 (Makishima et al., 1990; Coburn et al., 2005; Pottschmidt et al., 2005; Kreykenbohm et al.2005) and 4U0115+63 (Santangelo et al., 1999; Heindl et al., 2004) exhibiting 3 and 5 respectively. In most cases, the fundamental is broad and has been resolved, revealing a complex shape. As an indication of the power of the cyclomc modeling, for Cen X-3 (Fig. 2) we now directly measure a magnetic field of $B=3.46^{+0.07}_{-0.03}\times10^{12}$ Gauss, an electron thermal temperature for motion parallel to the magnetic field lines of $kT_e=7.04^{=0.63}_{-0.48}$ keV, the Thompson optical depth of the plasma (not the optical depth of the resonant scattering line) $\tau_T=2.4^{+0.05}_{-0.07}\times10^{-3}$, and a cosine of the angle of the line of sight to Earth and that of the magnetic field $\cos(\theta)=0.94^{+0.00}_{-0.07}$, or $\theta=20^{+10}_{-0}$ degrees from. *Furthermore, fitting spectra exhibiting multiple CRSFs with a model assuming a single magnetic field value validates the assumption that the spectral features are indeed due to CRSF harmonics and not due to sampling different regions with very different magnetic field values, i.e. 2, 3, 4, and 5 times the fundamental.*

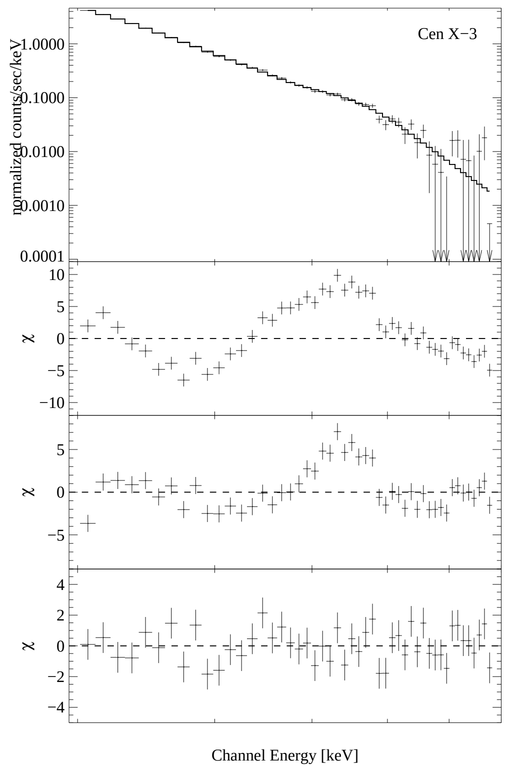

Figure 2: Fitting the *RXTE*/HEXTE spectrum of Cen X-3 with a continuum plus cyclomc model. The spectrum plus model is shown at the top, residuals to just a continuum model are shown just below with a fit with cyclomc included second from the bottom. The bottom set of residuals are for the addition of a partial covering of the cyclomc model to reduce the emission wings.

Detailed Modeling of the Continuum from First Principles: Modeling the continuum generated by accretion onto the magnetic poles of neutron stars is similarly very difficult because of the extreme physics of the flow structure, and to date empirical forms have been used. The radiation-dominated flow model (Davidson, 1973; Arons, Klein, & Lea, 1987) has shown considerable promise in accounting for the radiation properties of accreting X-ray pulsars. We already know that unlike the Coulomb collisional stopping and collisionless shock models (e.g. Langer & Rappaport, 1982), radiation-dominated flow models can account for the general shape of the X-ray spectra across a large range in accretion rate and X-ray luminosity. Such spectra have 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 the effects of Compton energization of the high energy photon distributions in the plasma. Fig. 3 shows the results from an analytic calculation of the spectrum of the accreting X-ray pulsar Her X-1 based on the radiation-dominated flow model (Becker & Wolff, 2007). This theoretical spectrum shows agreement with the observed spectrum over nearly 2 orders of magnitude in energy.

Accepting for the moment that the radiation-dominated shock model for the flows in these systems is correct, it is still very much the case that more work remains to be done in order to understand, from both a theoretical and observational perspective, the structure of the flows onto the magnetic polar caps of neutron stars in accreting X-ray pulsar systems. A critical assumption in the emerging theoretical development, 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 neutron star surface, fits 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 neutron stars go 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 similar to that posited by Becker & Kazanas (2001) in their study of the cosmic-ray acceleration in super-driven shock waves. Another question that is critical to 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 cyclotron photons in the mix of photon production mechanisms in the plasma (e.g., black body, and bremsstrahlung), 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. This aspect regulates the structure of the flows as it merges with the neutron star atmosphere. Work is proceeding on the structure and how the continuum is formed.

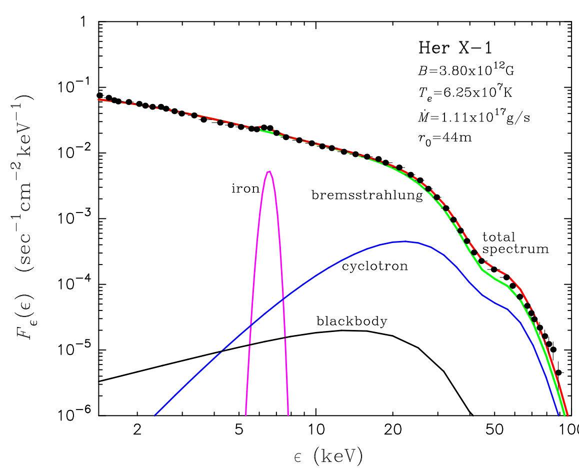

Figure 3: The theoretical column-integrated spectrum of Her X-1 evaluated using the radiative-shock model of Becker & Wolff (2007). The various components are labeled.

A New Development: the CRSF Energy-Luminosity Relationship: Details of the spectrum of Her X-1 have been studied for over 30 years. The history of the CRSF is shown in Fig. 4, including the discovery measurement(Trümper et al., 1977) and reanalysis of the *HEAO-1* data (Gruber et al., 2001), as well as modern-day measurements by *BeppoSAX, RXTE*, and *INTEGRAL*. Most striking is the transition around 1991 from a mean energy of 35 keV to one near 40 keV. An apparent reduction in the energy over time from the modern-day measurements can also be seen. Clearly, the neutron star magnetic field did not suddenly increase by 14%. The 12 *RXTE* measurements are plotted in Fig. 4 versus the maximum values of the *RXTE*/ASM count rate, and a clear correlation is seen (Staubert et al., 2007). The CRSF centroid is positively correlated with a measure of the Main-On luminosity, which is not subject to variations in the instantaneous flux due to absorption/shading by intervening material.

Measurements of the centroid-luminosity relationship have been made for other X-ray pulsars. They reveal the CRSF energy-continuum luminosity relation depends upon whether or not the luminosity is above or below a critical value. Two examples for a negative correlation between cyclotron line energy and luminosity are the high luminosity outbursts of the transients V 0332+53 and 4U 0115+63 (Mihara, 1995; Mowlavi et al., 2006; Nakajima, 2006; Tsygankov et al., 2006), in which the luminosity is clearly above the local Eddington limit, while the steady source Her X-1, with a luminosity clearly below the Eddington limit, shows the positive correlation (Staubert et al., 2007, Fig. 4). A 0535+26 is a source with luminosity in between and the cyclotron line energy is constant over a wide range in luminosity (Caballero et al., 2008). More data and theoretical work is necessary to understand this aspect of accretion onto the magnetic poles of neutron stars.

Requirements on Future X-ray Missions

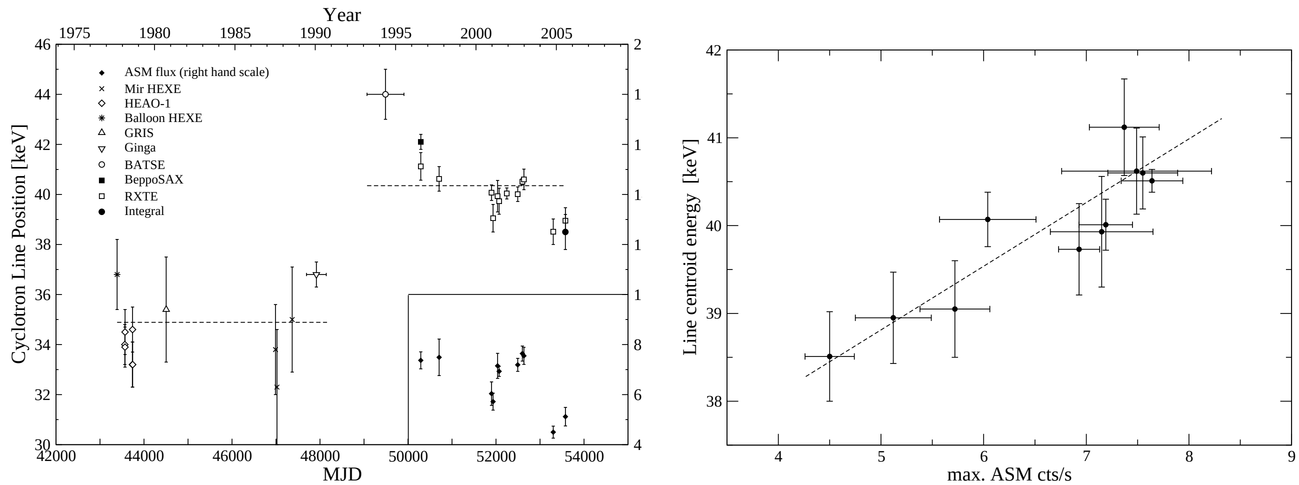

Figure 4: *Left*: The historical record of measurements of the Her X-1 CRSF energy versus time with the *RXTE*/ASM mean counting rate for the Main-on phase in which the CRSF is measured given on the left (Staubert et al., 2007). *Right*: The CRSF versus maximum flux of the corresponding Main-On as observed by the*RXTE*/ASM.

The physics of the polar cap of accreting X-ray pulsars is intimately tied to the mass accretion rate, the instantaneous viewing direction of the CRSF-forming region, and the formation of the pulse profile. We are just now beginning to have the physics-derived tools to follow-up on the basic character of the CRSF effects on the continuum radiation that we have learned since the discovery of CRSFs in 1977 (Trümper et al., 1977). In order to advance the understanding of the physical processes at the poles of accreting neutron stars, the science goals and the flow-down instrument requirements will need to be similar to those given in Table 1.

Table 1: Requirements Flow Down for CRSF Science

Parameter	value	Science Requirement
Energy Range	10 – 100 keV	Spans the range of known CRSFs
	2 – 10 keV	Provide continuum determination
Energy Resolution	ΔE/E$\leq$1 keV at 30 keV	Detect and measure emission wings
Time Resolution	$\leq 100\mu$s	Phase-connection over long observations
Sensitivity (2-10 keV)	10^{-11} ergs cm^{-2} s^{-1}	Track transients into quiescence
Maximum Sustained Counting Rate	~5 x Crab	Luminosity dependent CRSF energies
Pile-Up	$\leq$10% @5 x Crab	Luminosity dependent CRSF energies
Observing Plan	Flexible, repoint within one day	Response to transient X-ray pulsars

Missions presently under development, Astro-H in Japan, Simbol-X in Europe, and NuSTAR in the US meet some but not all of the requirements, and will provide important new discoveries from observations of neutron star X-ray pulsars. It will be important that IXO, AXTAR and other hard X-ray missions also have the hard X-ray capability expressed in Table 1, so that galactic X-ray binaries can be studied with the sensitivity necessary to make advances in our understanding of the processes involved in the accretion column above the magnetic poles of accreting X-ray pulsars.

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