On behalf of a large team...
Introduction

Accreting X-ray Pulsars
Accretion column properties
Observational features
Cyclotron resonant scattering
Accreting X-ray pulsar

Cen X-3 image by Dany Page

Cen X-3

~3 × 10^7 km

Sun

hot spot
A \sim 1 \text{ km}^2

accretion disk
few times 10^6 \text{ km}

magnetosphere
R \sim few 1000 \text{ km}

4.8 s
Accretion column properties

- Extreme energy density ($10^{37}$ erg/s in $\sim 1$ km$^3$).

- Very strong magnetic fields ($10^{12} - 10^{13}$ G) ➔ Exotic radiation processes possible. ➔ Very non-isotropic radiation transport.

- Many details uncertain, even geometrical structure!
Observational features

- Relatively simple spectra, with similar shape across sources and mostly stable in shape. Explained by cyclotron, bremsstrahlung and blackbody radiation, scattered by high speed electrons.

- Some sources (<20) show cyclotron line features as broad lines. Line position varies with luminosity for few sources.

- Pulse profiles quite different between sources. Sometimes stable for decades ("fingerprint"), sometimes very variable. No clear explanation for differences.

**Cyclotron line formation**

- Scattering of X-ray photons with quantized electrons in a strong magnetic field.
- Electron perpendicular momentum/energy restricted to Landau levels.
- Photons induce e transitions: "12-B-12 rule": \( \Delta E \approx 11.6 \ B_{12} \)

\[
E_n = m_e c^2 \sqrt{1 + \left( \frac{p}{m_e c} \right)^2 + 2n \frac{B}{B_{\text{crit}}}}
\]

\[
B_{\text{crit}} = \frac{(m_e^2 c^3)}{(\hbar e)} = 44.14 \times 10^{12} \text{ G}
\]

- Resonant cross sections
  - Photons at \( n\Delta E \) can hardly escape line forming region
  - Lines form in absorption

\( \Delta E \propto B \)

**Quasi-harmonic features**

**Diagnostic for \( B \)**
Cyclotron scattering cross-sections

- Difficult radiative transfer calculation because of strong dependence of cross section on energy and angle.

- Possible to redistribute photons from higher harmonics to fundamental line ("photon splitting").

Schwarm et al., 2012, INTEGRAL Workshop 2012
Recent Results

Luminosity regimes and cyclotron line variations

Pulse profile decomposition
Luminosity regimes

- ISSI Team Meeting between theorists and observers ➟ identification of luminosity regimes in accretion columns.

- Lowest luminosities: plasma hits surface or gets stopped in gas shock very close to pole.

- Above \( L_{\text{coul}} \approx [4-6] \times 10^{37} \text{ erg/s} \times B_{12}^{-1/3} \) (for \( M_{\text{NS}} = 1.4 \, M_{\odot} \) and \( R_{\text{NS}} = 10 \, \text{km} \)) plasma decelerated by Coulomb interactions.

- Above critical luminosity \( L_{\text{crit}} \approx [4-70] \times 10^{37} \text{ erg/s} \times B_{12}^{16/15} \) plasma decelerated by radiation pressure.

- Different reaction of columns and emission regions to luminosity changes, depending on regime, which depends on magnetic field.
Luminosity regimes & $E_{\text{cyc}}$ variations

Becker et al., 2012, A&A 544, A123
Comparison with observations

- Model explains different variations of $E_{\text{cyc}}$ in several transient sources by dominant braking process in column, driven by luminosity regimes.

- Caveat 1: Luminosities often quite uncertain (distance!)

- Caveat 2: small sample and serious doubts about results for 4U 0115+63! (Müller et al., 2013, A&A 551, A6)
Pulse profile modeling


- Assume axisymmetric emission from each pole and same beam pattern from both poles, but poles offset from antipodal position.

- Combination of accretion column, halo around hotspot, and scattering of photons in upper accretion stream.

- Non-unique decomposition → human judgement needed.
Current Developments

Tackling the bigger picture
Flexible cyclotron scattering models
Realistic relativistic light bending
Application: pulse peak phase shifts
Challenge: tackling the bigger picture

X-ray production
⇒ continuum $F_{\text{cont}}(E, \Theta)$

Photon/electron scattering
⇒ cyclotron lines $F_{\text{cont+lines}}(E, \Theta)$

GR Light bending & NS rotation
⇒ observed spectrum as function of phase $F_{\text{GR cont+lines}}(E, \Theta, \varphi)$
‘Hybrid’ column model

- Merging strengths of cyclotron MC model with column model.
- Column dimensions from Becker et al. (2012)
- Cyclotron layer sheath for small $\tau_{\text{Thom}}$, assuming dipole.
- Density and bulk velocity gradients from continuum calculations.
- Seed photons from continuum; angular redistribution by scattering.
Flexible cyclotron scattering model

- Schwarm et al.: Green’s function approach for cyclotron line scattering → apply to any continuum.

- Simulation of complex geometries → adapt to light-bending models.

- Photon tracing, treat micro-physics
Realistic relativistic light bending

- Falkner 2013 (PhD thesis): Software to describe observed flux from neutron star for arbitrary emission profile, accounting for special and general relativistic effects.
Application: pulse peak phase shifts

- Column + light-bending can be used to calculate flux as $F(E,\phi) = \text{phase-resolved spectra} = \text{energy-resolved pulse profiles}$ for any set-up.

- Schönherr et al. (submitted): observed shifts in pulse profile peaks around cyclotron line energies can result as a direct consequence of cyclotron resonance scattering plus relativistic bulk motion of plasma.
Conclusions

- Exciting times for study of accretion column in X-ray pulsars.
- Increased computing resources and improved methods yield new tools for modeling of observations.
- Encouraging results, but also much increased complexity of factors to be taken into account!
- Need to identify best observables to test model results.