Cyclotron Line Sources with *RXTE, INTEGRAL, Suzaku, BeppoSAX*

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on behalf of the Magnet collaboration
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RXTE Workshop, Washington DC, November 5th, 2009
Accreting Pulsars

a few \times 10^{12} \, \text{G}
mainly HMXBs
\sim 17 \, \text{sources}
\sim 50\% \, \text{transient}

- wind accretion
dips & flares
- Be accretion
normal & giant outbursts

Negueruela, based on
Davidson & Ostriker (1973)
Spectrum

**X-Ray Spectral Shape**

- **power law** continuum with exponential cutoff
- Compton scattering
- **often strong Fe Kα line** at 6.4...6.7 keV fluorescence in circumstellar material
- cyclotron line
- strong B-field
- luminosity & pulse phase dependence

Trümper et al. (1978a)
Continuum Production

**Becker & Wolff (2005a,b, 2007)**

**Bulk motion and thermal Comptonization** of seed photons:

- accretion mound produces soft X-rays (*bremsstrahlung, cyclotron, blackbody*)
- X-rays are upscattered in **accretion shock**
- hard X-rays diffuse through walls of accretion column

Continuum Modeling

- current – empirical: $E^{-\Gamma}$ with cutoff
- future – physics: see above
Physical Continuum: Example

4U 0115+63, *BeppoSax*, Ferrigno et al., 2009

Becker and Wolff continuum model is now available for spectral fitting.
Line Production

Quantization of electron energies \( \perp B \)-field lines, for \( B \ll \sim 4.4 \times 10^{13} \text{ G} \), distance between Landau levels:

\[
E_{\text{cyc}} = \frac{\hbar e}{m_e c} B = 11.6 \text{ keV} \left( \frac{B}{10^{12} \text{ G}} \right)
\]

\( \Rightarrow \) Cyclotron Resonance Scattering Features ("cyclotron lines") at

\[
E_n = nE_{\text{cyc}} = (1 + z)E_{n,\text{obs}}
\]

Line Modeling

- current – empirical:
  Gaussian optical depth profile
- future – physics:
  Monte Carlo \( (kT_e, \tau_{es}, B, \mu) \)

Schönherr et al. (2007)

Work in progress by F. Schwarm.
Physical Line: Example

**Line Model – cyclomc**

- $B = 3.05 \times 10^{12} \, \text{G}$
- $kT_e = 10.2 \, \text{keV}$
- $\tau_{es} = 0.003$, $\mu = 0.06$

**Continuum – fdcut**

- $\Gamma = 0.94$
- $E_{\text{cut}} = 12.8 \, \text{keV}$
- $E_{\text{fold}} = 7.5 \, \text{keV}$

**Geometry**

- accretion column = bottom illuminated slab;
- partial covering

**V0332+53, INTEGRAL, Schönherr et al. (2007)**
4U 1907+09 with INTEGRAL and Suzaku

\[ \dot{P}_{\text{pulse}} \text{ with RXTE, INTEGRAL, Suzaku} \]

two recent torque reversals

(Baykal et al, 2006, 2009; Fritz et al. 2006; Rivers et al., 2009, submitted)

19 keV cyclo & Fe with Suzaku

19, 40 keV cyclo with INTEGRAL

40 mCrab source
Centaurus X-3 with *Suzaku* and *RXTE*

One binary orbit with *Suzaku* in 2008 2nd half suppressed
(Suchy et al., 2010, in prep.)

Two binary orbits with *RXTE* in 1997
pulse phase dependence of $E_{cyc}$ not consistent with dipole
(Suchy et al., 2008)
Swift J1626.6−5156 with RXTE (\& Swift)

discovered 2005 (Krimm, 2005)
oscillations (Reig et al., 2008)
changing $P$ (DeCesar et al., ATEL #2036)
132.9 d orbit (Baykal, ATEL #2250)

cyclotron lines at $\sim 10$ keV and $\sim 18$ keV
(DeCesar et al., 2009, submitted)
A0535+26 with *RXTE* (& *INTEGRAL*, *Suzaku*)

- **Normal outburst in 2005** following giant outburst
  - $E_{\text{cycl}}$ increased during pre-flare
  - (Caballero et al., 2007, 2008)

- **Normal outburst in 2009**
  - Two-peaked, 2nd peak @ periastron
  - $E_{\text{cycl}}$ constant
  - (Caballero et al., 2009, in prep.)
Luminosity versus $E_{\text{cycl}}$

Mihara et al. (2007), Nakajima et al. (2008)
MXB 0656-072 added by Dauser (2008)
work in progress
Summary & Outlook

- **Continuum Emission** – improve & test physical model
- **Cyclotron Lines** – improve & test physical model
- **Observations** – increase coverage of: **Time, Energy, Luminosity, Phase**
- **Wind Signatures** – observe & model
- **Outburst Cycles** – observe & model
- **Important Diagnostics:**
  - spectra (**pulse**, orbit, time) **resolved**
  - pulse profiles, lightcurves (energy resolved)
  - **luminosity** – $E_{\text{cycl}}$ relationship
  - $E_{\text{cycl}}$ spacing for harmonics
  - "10 keV bump"
  - flare distributions
### Table: Source Parameters

<table>
<thead>
<tr>
<th>Source</th>
<th>$E_{\text{cyc}}$ [keV]</th>
<th>$P_{\text{pulse}}$ [s]</th>
<th>$P_{\text{orb}}$ [d]</th>
<th>type</th>
</tr>
</thead>
<tbody>
<tr>
<td>4U 0115+63</td>
<td>14, 24, 36, 48, 62</td>
<td>3.6</td>
<td>24.31</td>
<td>T, Be</td>
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<tr>
<td>V 0332+53</td>
<td>27, 51, 74</td>
<td>4.37</td>
<td>34.25</td>
<td>T, Be</td>
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<td>A0535+26</td>
<td>45, 100</td>
<td>105</td>
<td>110.58</td>
<td>T, Be</td>
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<td>Vela X-1</td>
<td>25, 53</td>
<td>283</td>
<td>8.96</td>
<td>P, B0.5 Ia</td>
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<tr>
<td>4U 1907+09</td>
<td>19, 40</td>
<td>438</td>
<td>8.38</td>
<td>P, B2 III–IV</td>
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<td>Swift 1626.6−5156</td>
<td>10, 18</td>
<td>15.35</td>
<td>132.9</td>
<td>T, Be</td>
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<tr>
<td>4U 1538−52</td>
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<td>530</td>
<td>3.73</td>
<td>P, B0 I</td>
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<tr>
<td>X Per</td>
<td>29</td>
<td>837</td>
<td>250.3</td>
<td>P, B0 III–Ve</td>
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<tr>
<td>Cen X-3</td>
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<td>2.09</td>
<td>P, O6.5 II</td>
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<td>OAO 1657−415</td>
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<td>10.4</td>
<td>P, B0-B6 Ia-lab</td>
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<td>GX 301−2</td>
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<td>7.66</td>
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<td>P, WD?</td>
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<td>Her X-1</td>
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<td>1.24</td>
<td>1.7</td>
<td>P, A9-B</td>
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<td>EXO 2030+375</td>
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<td>42</td>
<td>46.0</td>
<td>I, B0 Ve</td>
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<td>Cep X-4</td>
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<td>66.25</td>
<td>&gt;23</td>
<td>T, B1</td>
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<tr>
<td>MXB 0656-072</td>
<td>33</td>
<td>160.4</td>
<td>–</td>
<td>T, O9.7 Ve</td>
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<tr>
<td>XTE J1946+274</td>
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<td>15.8</td>
<td>169.2</td>
<td>T, B0-1 V-IVe</td>
</tr>
</tbody>
</table>

Candidates: 2S 1417−624 (T), 1A 1111−616 (T), GRO J1008−57 (T), AX J1749.1−2639 (T), XTE J1739−302 (T), GX 1+4 (P), 4U 2206+54 (P), 4U 1909+07 (P), 4U 1700−377 (P), LMC X-4 (P), + ∼ 10 transients