Study of cyclotron line sources, the present and the future.
Outline

• A quick summary

• A theoretical study on the origin of cyclotron line energy flux dependency

• New INTEGRAL determination of a positive flux-centroid energy in GX 304-1

• IGR J18179-1621: a new cyclotron source?

• RX J0440.9+4431: a new cyclotron line source.

• Prospects for future missions.
High B-field: an ubiquitous phenomenon

- Low mass X-ray binaries normally associated with low-B ($10^{8-9}$ G) neutron star (old systems). An exception is, e.g., Her X-1
  - Roche lobe overflow -> accretion disk
  - transient or persistent

- High mass X-ray binaries are normally young systems, where NS has a high B-field ($10^{12-13}$ G)
  - wind-fed systems but with formation of transient accretion disk
  - transients or persistent

- Be-Xray binaries are very important, as they become very bright during outbursts and give high S/N

$$\frac{L_{\text{outburst}}}{L_{\text{quiescence}}} \sim 10^3$$
Some famous sources

Be-binaries

• 4U 0115+63:
  – B ~ 10^{12} G, the lowest
  – Fundamental cyclotron line plus 5 higher harmonics detected
  – P_{\text{spin}}=3.6 \text{ s}. Spectrum is highly variable with spin phase.

• V 0332+53:
  – B ~ 2\times 10^{12} G, 3 harmonics
  – P_{\text{spin}}=4.4 \text{ s} not very variable with spin phase

• A 0535+262:
  – B ~ 5\times 10^{12} G, 2 harmonics
  – P_{\text{spin}}= 103 \text{ s}

Roche lobe overflow

• Her X-1:
  – B ~ 4\times 10^{12} G
  – Fundamental cyclotron line plus 1 higher harmonic
  – P_{\text{spin}}=1 \text{ s}. Spectrum is highly variable with spin phase and superorbital modulation
Emission mechanisms in a high magnetic field

- Accreting matter acquires a high kinetic energy $v \sim c/2$ which is partially dissipated close to the compact object surface and emitted in the form of X and Gamma-rays.

- If the neutron star has a considerable magnetic field, the accreting matter is channeled at the magnetic poles along the field lines and accretes on the poles.

- For high accretion rates, radiation dominates: a radiative shock and accretion column form.

- Seed photons coming from thermal mound and electron bremsstrahlung, in the high B-field, are Compton scattered.

Becker & Wolff (2007)
Electrons are exited to the first Landau level and then re-emit.

To be observed in the X-ray domain, a B-field of $10^{12-13}$ G is required.


\[ E_n = m_e c^2 \sqrt{1 + 2n(B/B_{\text{crit}}) \sin^2 \theta - 1} \frac{1}{\sin^2 \theta \left(1 + \frac{1}{z'}\right)} \]

$4.4 \times 10^{13}$ G

Cyclotron lines

Kreikenbohm et al. (2005)

V 0332+53

Isenberg et al. (1998)
Continuum physical model

• One long BeppoSAX observation in 1999. We introduced the cyclotron emission model, and added a lower energy Comptonization component. Satisfactory description of the properties of 4U 0115+634.

Thermal Comptonization of 0.5 keV BB
\[ T_e \sim 2-3 \text{ keV} \]
CompTT

Gaussian to correct the rough modeling

Thermal and bulk Comptonization of cyclotron emission.
\[ T_e \sim 6-10 \text{ keV} \]
\[ B \sim 0.6-0.8 \times 10^{12} \text{ G} \]
(Becker & Wolff, 2007)

Ferrigno et al. (2009)
Soft scattering halo?

- Pronounced phase variations of continuum and lines.
- Hard component prominent in the peak, soft component spread in phase: a scattering halo?

Ferrigno et al. (2009)
• RXTE/INTEGRAL data in 3-100 keV band
• Anti correlation with luminosity
• Radiation enlarges the column

V 0332+53

Her X-1

• RXTE data of main-on (obscuration from disc)
• Correlation with luminosity
• Accretion squeezes the column
Pulse to Pulse Variability

- During the bright phase (!) of an outburst
- Rate resolved spectroscopy reveals trend!
- Evidence of different accretion regimes in four bright sources

Klochkov et al (2011)
Different accretion regimes

- Column is a region magnetically confined
- Depending on its width and amount of accretion, radiation can play an important role.
- Eddington limit must be adapted for the geometrical and cross section effects

$L_{\text{Edd}} = \frac{4\pi G M_\ast m_p c}{\sigma_T}$

$\frac{\pi r_0^2}{4\pi R_*^2} = \frac{GM_\ast m_p c}{\sigma_\parallel} \frac{\pi r_0^2}{R_*^2}$
A critical luminosity

\[ L_{\text{crit}} = \frac{GM_* m_p c}{\sigma_{||}} \frac{\pi r_0^2}{R_*^2} \left( \frac{R_*}{49H} + 1 \right). \]  

\text{Height of the radiative shock}

Our goal is to express the parameters \( r_0, \sigma_{||}, \) and \( H \) appearing on the right-hand side of Eq. (9) in terms of observable quantities.

- Equation is derived following Basko & Sunyaev (1977) by:
  - assuming a strong radiative shock (\( L > L_{\text{Edd}} \))
  - free-fall velocity (\( v_{\text{ff}} \)) upstream and \( v_{ps} = 1/7 v_{\text{ff}} \) downstream
  - constant deceleration below the shock
  - radiation braking

\[ a = \frac{v_{ps}^2}{2H} = \frac{GM_*}{49R_* H}. \]

\[ a = \left( \frac{L_X}{L_{\text{Edd}}^*} - 1 \right) \frac{GM_*}{R_*^2}. \]

Becker et al. (2012)
• Use the surface magnetic field and assume a dipole structure, a variation of the emission height translates into a variation of the observed cyclotron scattering centroid energy

\[
E_\ast = 11.58 \text{ keV} \left( \frac{B_\ast}{10^{12} \text{G}} \right)
\]

\[
\frac{E_{\text{cyc}}}{E_\ast} = \left( \frac{R_\ast + h}{R_\ast} \right)^{-3}
\]

• where h is \( h_s \) or \( h_c \) in the two regimes

Comparison to data

Becker et al. (2012)
Comparison to data

Becker et al. (2012)

<table>
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<tr>
<th>Source</th>
<th>Long-term $\xi$ [keV]</th>
<th>Long-term $L_{\text{crit}}$ [$10^{37}$ erg sec$^{-1}$]</th>
<th>Pulse-pulse $\xi$ [keV]</th>
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4U 0115+63, is the line variation real?

• Only the fundamental shows a variation, the higher harmonics are stable!! -> fit is wrong (2008 outburst using NPEX continuum model)

Li et al. (2012)
• I call it Wrong !!!!!
• Large sigma in Gaussian or width in Lorentzian lines.

\[ \text{NPEX}(E) = (A_1 E^{-\alpha_1} + A_2 E^{+\alpha_2}) \exp \left( -\frac{E}{kT} \right), \]
High energy cut-off PL

- Still artificial suppression of continuum

\[
I_{\text{cont}} = K \cdot \begin{cases}
E^{-\Gamma}, & \text{if } E \leq E_{\text{cutoff}} - \Delta E \\
E^{-\Gamma} \cdot \exp\left(-\frac{E - E_{\text{cutoff}}}{E_{\text{fold}}}\right), & \text{if } E > E_{\text{cutoff}} + \Delta E \\
AE^3 + BE^2 + CE + D, & \text{if } E_{\text{cutoff}} - \Delta E < E < E_{\text{cutoff}} + \Delta E,
\end{cases}
\]
High-E cut-off PL + 9 keV Gaussian

\[
I_{\text{Model}} = I_{\text{cont}} + K_{\text{bump}} \exp\left\{-\frac{(E - E_{\text{bump}})^2}{2\sigma_{\text{bump}}^2}\right\},
\]

- More correct
• Adopt a more complex continuum, so that the lines do not fudge the continuum itself

Mueller, Ferrigno et al. (in prep)
Luminosity dependency vanishes

- Coherent fundamental and first harmonic non-variation

Mueller, Ferrigno et al. (in prep)
• Outburst in 2011 when it reached Crab-like flux

• A flux-cyclotron line positive correlation has been reported during previous outbursts using Suzaku and RXTE

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Klochkov et al. (2012)
Positive correlation

- Beautiful measures of another subcritical system
A new cyclotron source?

- IGR J18179-1621 discovered during quick-look (ATeL #3947)
- Observed by INTEGRAL serendipitously
- Swift/XRT follow-up campaign
- Strong indication of a cyclotron line at ~20 keV

Bozzo, Ferrigno et al. (2012)
Difficult timing study

Data

Simulations
Timing results

- Estimate confidence of determination using MC simulation and $Z^2$ statistics technique
- At 99% c.l., we can retain just 4 out of 9 determinations

Bozzo, Ferrigno et al. (2012)
• Classified as persistent Be/X-ray binary at 3.3 kpc distance
• Series of flares separated of ~155 days in 2010-2011
• Three papers published and one in preparation
A dip-like structure at high L

• A dip-like structure appeared during the first outburst at soft X-rays
• Interpreted as due to occultation from the accretion stream
• Introduced a very soft BB for a better fit (the accretion stream?)
A cyclotron absorption in INTEGRAL

- Hard X-ray coverage by INTEGRAL of second outburst
- Discovery of an absorption feature due to cyclotron scattering
- Magnetic field strength confirmed by PSD analysis.
Analysis of Swift/BAT data confirms periodicity and gives a typical Be/X-ray binary orbital light curve $P_{\text{orb}}=(147.9+/-0.3)$
RXTE-Swift/XRT follow-up

- Spectral hardening as function of luminosity, the same in three outbursts, due to high $E_{\text{cut}}$ and larger BB area
- Spectrum is combination of BB+cutoffPL with low absorption $N_H \sim 0.7 \times 10^{22} \text{ cm}^{-2}$
- BB not detectable at low luminosity with RXTE but detected in quiescence by XMM-Newton (La Palombara et al., 2011)
BB radius and luminosity

- BB radius increases with L, as expected in disk-fed systems.
- slope is steeper than expected if BB radius is coupled with magnetospheric radius.
- At highest luminosity, decrease?

\[ r_0 = 1.93 \times 10^5 \text{ cm} \left( \frac{\Lambda}{0.1} \right)^{-1/2} \left( \frac{M_*}{1.4 M_\odot} \right)^{-1/14} \left( \frac{R_*}{10 \text{ km}} \right)^{11/14} \times \left( \frac{B_*}{10^{12} \text{G}} \right)^{-2/7} \left( \frac{L_*}{10^{37} \text{erg sec}^{-1}} \right)^{1/7} \]
Future
• 4U 0115+63 in outburst, fit with a complex model using Beppo-SAX broad-band data (45 ks)
• Astro-H will provide in 10 ks a better constraints on relevant parameters (line width at 0.2 keV) and a slightly larger band!
• Smaller band prevents continuum study, but large effective area provides spectral ability on one pulse time-scale.
• Line centroids at better than 1 keV in 3.6s exposure!
• Variability study at pulse time scale -> trace accretion.
Conclusions

• The presented theoretical study furnishes a robust understanding of the cyclotron line flux dependency in different sources with different trend.
• We also demonstrated that in the case of 4U 0115+63, the observational result is doubtful.
• The use of archive data is limited and it would be important to discover more sources showing this effect.
• It is essential to use a facility with high-energy coverage as INTEGRAL and Suzaku (Astro-H and LOFT in the future).
• However, Suzaku normally does not provide extended coverage of an outburst as INTEGRAL.