Secular change of the cyclotron line energy in Hercules X-1

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Outline

• Introduction to Her X-1
• Cyclotron line
• Variability of the cyclotron line energy $E_{cyc}$
• Secular decay of $E_{cyc}$: a new phenomenon
• Speculations / Questions
• Summary

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Statements about Her X-1

- Best studied XRBPs (luminous, relat. near, persistent)
- Together with Cen X-3 first detected XRBPs (Uhuru 1972)
- First XRBPs with cyclotron line (CRSF) (Trümper et al. 1976)
- First XRBPs with \( E_{cyc} \) prop. \( L_x \) (Staubert et al. 2007)
- First XRBPs with \( E_{cyc} \) showing secular decay (Staubert et al. 2014)
Accreting binary X-ray pulsar with Roche-lobe overflow

source: J. Trümper
Discovery of the first Cyclotron Line

Balloon-HEXE observation
Texas, 3 May 1976
(Trümper et al. 1977, 1978)

First direct measurement of the field strength of a NS:

\[ B \approx 3 \times 10^{12} \text{ Gauss} \]

Today we know ~25 objects with cyclotron lines

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**Cyclotron Resonant Scattering Feature (CRSF)**

\[ E_{\text{cyc}} = \frac{n \hbar e/m_e c}{11.6 \text{ keV}} B \]

\[ = n \frac{11.6 \text{[keV]}}{B \text{[Gauß]}/10^{12}} \]

\[ B_{12} = \frac{(1+z) E_{\text{obs}}}{11.6 \text{ keV}} \]

\[ z \] gravitational redshift

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Cyclotron Resonant Scattering Feature (CRSF)

Accretion Mound

Continuum photons trying to escape from the hot mound are resonantly scattered by electrons at the cyclotron energy and are therefore missing in the observed spectrum.

absorption line

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Variability of $E_{\text{cyc}}$

The cyclotron line Energy $E_{\text{cyc}}$ varies with:

- pulse phase (not discussed here)
- 35d phase (not discussed here)
- luminosity
- time (secular variation)

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Long-term evolution of $E_{\text{cyc}}$

is the apparent decay of $E_{\text{cyc}}$ with time real?

Staubert et al. 2007
A&A 465, L25
Positive correlation of $E_{\text{cyc}}$ with $L_x$

$E_{\text{cyc}}$ [keV] = $40 + 0.66 \times (\text{max. ASM cts/s} - 6.8)$

$E_{\text{cyc}}$ increases by ~7% for a factor of 2 increase in $L_x$


R. Staubert 10th INTEGRAL Workshop, Annapolis, Sept 2014
Her X-1: normalized cyclotron line energy vs. time

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Negative correlation of $E_{\text{cyc}}$ with $L_x$

$E_{\text{cyc}}$ drops by $\sim7\%$ for a factor of 2 increase in $L_x$

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Two accretion regimes

\[ L_X > L_{\text{crit}} \quad \text{height increases for increasing } L_X \]

\[ L_X < L_{\text{crit}} \quad \text{height decreases for increasing } L_X \]

\[ L_{\text{crit}} \sim 10^{37} \text{ erg/s} \]

Observations:
Klochkov et al. 2011, A&A 532, 126

Theory:
Basic idea for $E_{\text{cyc}}$ versus $L_x$

- **negative correlation for $L_x > L_{\text{crit}}$**
  - deceleration by radiation $\Rightarrow$ height of line-forming region increases with incr. $M_{\text{dot}}$

- **positive correlation for $L_x < L_{\text{crit}}$**
  - deceler. by Coulomb drag $\Rightarrow$ height of line-forming region decreases with incr. $M_{\text{dot}}$
Long-term evolution of $E_{\text{cyc}}$

Her X-1

The apparent decay did continue

Fig. 4
in Staubert et al. 2014
A&A in press
arXiv: 1410.3647

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Positive correlation of $E_{\text{cyc}}$ with $L_x$. update 2014

Fig. 1
in Staubert et al. 2014
A&A in press
arXiv: 1410.3647

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**Her X-1: normalized cyclotron line energy vs. time secular variation**

Fig. 5 in Staubert et al. 2014 A&A in press arXiv: 1410.3647

mean(<2007) = 40.1 +/- 0.1 keV

difference: >17 sigma

mean(>2007) = 37.6 +/- 0.1 keV

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Her X-1: cyclotron line energy vs. flux and time

fit with two variables

best fit with two variables (Flux and Time): $E_{\text{cyc}} = E_0 + a \cdot (F - F_0) + b \cdot (T - T_0)$

$E_0 = (39.25 \pm 0.07) \text{ keV}$

$a = (0.44 \pm 0.09) \text{ keV/(ASM-cts/s)}$

$b = (-7.22 \pm 0.39) \times 10^{-4} \text{ keV/d}$

$F_0 = 6.8 \text{ ASM-cts/s}$

$T_0 = \text{MJD 53500}$

$b = -5 \text{ keV in 20 yrs}$

Fig. 6 in Staubert et al. 2014
A&A in press
arXiv: 1410.3647

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Physics of the $E_{\text{cyc}}$ change with time ??

Ideas (comments /questions):

- Change of the global dipole field of the NS? unlikely
  more likely a local phenomenon:
  - Accretion mound structure changes due to continuous accretion?
    - increase of the height of the accretion mound? dipol: -5 keV means +400 m !?
      model: +few m in height ---> large changes in $B_{\text{max}}$
    - hot spot area is increased, B-field is diluted? (-13% in 20 yrs)
    - B-field is "screened" or "buried"? total mass needed? time scale?

- "Ohmic dissipation" of B-field? on "diffusion" time scale: $t = 4 \pi R^2 \sigma c^2$, needs small R and small sig!
- Thermo-magnetic effects or Hall effect? heating due to accretion?
- ?????

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Basic questions about accretion onto NSs

Assume continuous accretion (e.g. $10^{17}$ g/sec):
- what happens to the accreted material? does it accumulate?
- is the material "incorporated" into the crust?
- is the accretion mound static - in "equilibrium"?
- can the accretion mound grow or shrink (height/total mass)?
- can the B-field configuration change? (e.g. "ballooning")
- does material "leak out" to the sides at the base of the accretion mound?
- how much total mass can be "stored" in the mound?
  (until the B-field "breaks")
- can the B-field be "screened" or "buried"?
- what is the dynamical evolution of the mound?

Why does Ecyc increase with Lx?
Why does Ecyc decrease with time?

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Long-term behavior of $E_{\text{cyc}}$ ??

Her X-1

does $E_{\text{cyc}}$ possibly follow a cyclic behavior on long time scales?

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**Summary**

1) confirmed:
   Positive correlation of $E_{cyc}$ with $L_x$ (co-existing with decay)
2) new:
   Decay of $E_{cyc}$ with time (on time scale of tens of years)
3) future:
   Cyclic behavior of $E_{cyc}$ with time ??

**Challenge for theorists:**
   Understand physics of B-field change

**Challenge for observes:**
   Continue to monitor Her X-1
   Find more objects with $E_{cyc}$ time variation

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Thank you for your attention