Neutron Star Binaries

~ Cyclotron Resonances Revisited ~

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Suzaku 2007 San Diego
**CRSF (cyclotron resonance scattering feature)**

- A spectral feature due to $e^-$ transitions between adjacent Landau levels in a magnetic field $B$, observed at an energy of $E = 11.6 \ (B/10^{12}\text{G})$ keV.

- Detected all in absorption from ~15 accreting pulsars, with balloons, *HEAO-1, CGRO, Ginga* (2 reconfirm., 5 discoveries; Mihara 95), *BeppoSAX, RXTE, INTEGRAL, Swift, and Suzaku*.

- Provides the most accurate estimates of NS surface magnetic fields, with clean and important fundamental physics.

The measured $B$ (Makishima + 99);
- Concentrated over $(1-4) \times 10^{12}$ G.
- Argue against “field decay” hypothesis.
- Suggest “ferromagnetism” in nuclear matter.
Recent Progress

- Three harmonic absorption lines from X0331+53 (Pottschmidt+05), after 4U 0115+63.
- $L_x$-dependent changes in $E_a$ (Mihara+04; Nakajima+06, 08; Tsygankov+06; Mowlavi+06) --> Column gets taller as $L_x$ increases.
- $L_x$-dependent change in the $E_2/E_1$ ratio (Nakajima+08) --> The 2nd harmonic, with a smaller cross section, has a "photosphere" closer to the NS surface.

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Suzaku observations of CRSF: Crab ratios

- A0535+26
- PIN: 10 mCrab
- GSO
- 22 ks (05/09/14)

- Her X-1 (on-off)
- 2005: 30 ks (05/10/05)
- 2006: 34 ks (06/03/29)

- Reconfirm Orlandini+98
- 10 mCrab
- 100 ks (06/03/09)

- 4U 1626-67
- 100 ks (06/03/09)

- 10 mCrab

- GRO J1008-57 TOO; 2007/11/30

Cyclotron Resonance Profiles

A forced oscillation of an electron in a uniform magnetic field $B$;

$$m \frac{d\mathbf{v}}{dt} = -e \mathbf{v} \times \mathbf{B} - m \Gamma \mathbf{v} + E_0 e^{i\omega t}$$

Classical scattering cross section of the incident EM radiation;

$$S(E) = D \left( \frac{W}{E_a} \right)^2 \frac{E^2}{(E - E_a)^2 + W^2}$$

(1) Use $S(E)$ itself, assuming $W$ gets somehow larger (Clark+09)

$\rightarrow$ CYAB modeling;

$$CYAB(E) = \exp\{-S(E)\}$$

(2) Assuming thermal Doppler effects dominate, convolve $S(E)$ with a Gaussian

$\rightarrow$ Gabs modeling

$$Gabs(E) = \exp\left\{-\tau \exp\left(-\frac{(E - E_c)^2}{2\sigma^2}\right)\right\}$$

The natural width (radiative de-excitation rate of an excited Landau level) is small; $W \ll E_a$
The NPEX Continuum Model

- Negative & Positive powerlaws with Exponential (Mihara 1995):
  \[ f(E) = \left( A - E^{-\alpha} + A^+ E^+\beta \right) \exp(-E/E_{\text{cut}}) \]

  - Unsaturated saturated

- An approximation to thermal Compton emission with multiple optical depths.
  - \( \beta = 2.0 \) if in the Wien regime.

- Successful on many accreting pulsar continua (Makishima+ 99).

The best-fit double Compton model for Cyg X-1, as determined with Suzaku (Makishima + 08, PASJ, submitted)
Positive detection at $E > 2E_a$ implies --
- A relatively hard NPEX envelope
- Evidence for the 2nd harmonic
- Strong attenuation between $E_a \sim 2E_a$

Little dependence on the absorption model
Higher-Lx / Lower-field sources with RXTE

4U 0115+63 Crab ratio (Nakjima + 06)

The same spectral structure in higher-Lx and lower-field sources.
Absorption Profile: CYAB or Gabs?

When $\exp(-S)$ is plotted logarithmically, it directly reveals $S$ in linear form.

X0331+53 with RXTE: Data/(NPEX envelope)

The origin of CYAB must be fixed.

Two Gabs factors

Two CYAB factors

Energy (keV) in linear scale

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We (Kitaguchi +) found a bug in the Gabs model in Xspec 11.3, and reported it to HEASOFT in late November 2007.

In calculating the multiplicative Gabs model as
\[ m = \exp\{-aG\}, \]
the current routine utilized the additive Gaussian line model as
\[ G = \exp\{-0.5 (E-b)^2/c^2\}, \]
where \( G \) is returned in units of photons/cm\(^2\)/s, instead of photons/cm\(^2\)/s/keV which should be used in multiplicative models. As a result, \( G \), hence \( m \), became dependent on the bin width.

Hereafter, we use a local Gabs model where the bug is fixed.
### Fit Results & Goodness

**X0331+53 with RXTE**

**CYAB x CYAB**

- $E_{\text{cut}} = 6.78$
- $E_1 = 23.3$, $E_2 = 49.2$
- $D_1 = 1.39$, $D_2 = 1.3$
- $W_1 = 7.7$, $W_2 = 6.3$

- $\chi^2/\nu = 1.96$ ($\nu = 77$)

**Gabs x Gabs**

- $E_{\text{cut}} = 6.05$
- $E_1 = 25.7$, $E_2 = 48.9$
- $\tau_1 = 0.57$, $\tau_2 = 0.38$ (too shallow)
- $\sigma_1 = 4.9$, $\sigma_2 = 8.0$ (too wide)

- $\chi^2/\nu = 2.69$
- $\Delta\chi^2 = 58.5$

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**Her X-1 (on-off) Suzaku**

**Enoto+08**

- $E_{\text{cut}} = 11.4$
- $E_1 = 37.5$
- $D_1 = 2.1$, $D_2 = 1.7$
- $W_1 = 14.0$, $W_2 = 17.7$

- $\chi^2/\nu = 1.18$ ($\nu = 354$)

**CYAB2**

- $E_{\text{cut}} = 11.0$
- $E_1 = 42.8$
- $\tau_1 = 1.5$, $\tau_2 = 2.3$
- $\sigma_1 = 10.6$, $\sigma_2 = 19.4$

- $\chi^2/\nu = 1.40$
- $\Delta\chi^2 = 76.3$
**Discussion & Summary**

*Suzaku* observations of dimmer and/or higher-field sources:
- Clear signal detections of at $E > 2E_a$ with **HXD-GSO**.
- **HXD-PIN** measurements of the fundamental resonance with good $\Delta E$.

**Consequences:**
1. The fundamental resonance strong, with $D_1 = 1.3-2.0$
2. The 2nd resonance ubiquitous, with $D_2 \sim D_1$.
3. CYAB successful on profile modeling, but Gabs not.
4. Strong flux suppression been $E$ and $2E_a$.
5. Theoretically predicted “red/blue wings” not seen.

**The origin of resonance width:**
1. Thermal Doppler-- unlikely to account for 100%.
2. Phase-dependent changes in $E_a$ -- not dominant.
3. Uncertainty principle + unexpectedly short life times of the excited Landau level (**Enoto+08**) -- Possible?
GX 349+2 observed with *Suzaku* in Flaring Branch (2.8 ks)

MCD \((T_{\text{in}} \sim 1.0 \text{ keV}, r_{\text{in}} \sim 25 \text{ km})\)
BB1 \((T \sim 1.6 \text{ keV}, r \sim 15 \text{ km})\)
BB2 \((T \sim 2.7 \text{ keV}, r \sim 5 \text{ km})\)
Gau \((\sim 6.7 \text{ keV}, \sigma \sim 0.4 \text{ keV}, \text{EW} \sim 70 \text{ eV})\)

**GX 349+2**

**GX 5-1**

**Opt.thick outflow**

**Truncated cool disk**

**Luminous LMXXB**