Discovery and Model of a Rollover in the Positive Cyclotron Line/Luminosity Relation in GX 304−1 with *RXTE*

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Abstract

The *RXTE* observed four outbursts of the accreting X-ray binary transient pulsar, GX 304−1 in 2010 and 2011. We present results of detailed 3−100 keV spectral analyses of 69 separate observations, and report a positive correlation between cyclotron line parameters and luminosity, as well as other spectral parameters' correlations with luminosity. The cyclotron line energy, width and depth versus luminosity correlations show a flattening or roll-over of the relationships with increasing luminosity, which are well described by quasi-spherical or disk accretion. The accretion mound/column X-ray flux is found to be in the Coulomb braking regime. Since HEXTE cluster A was fixed aligned with the PCA field of view and cluster B was fixed viewing a background region 1.5 degrees off of the source direction, the cluster A background was estimated from cluster B events. This made possible the detection of the ~55 keV cyclotron line and an accurate measurement of the continuum at energies above the line. Correlations of all spectral parameters with primary 2−10 keV power law flux reveal the mass accretion rate to be the primary driver of the spectral shape.

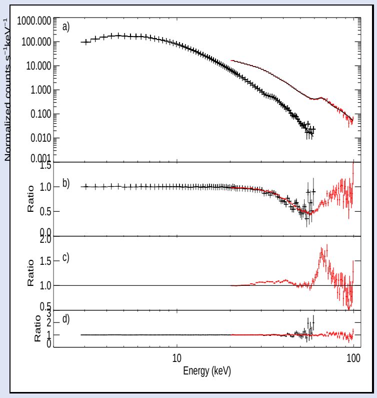
Introduction

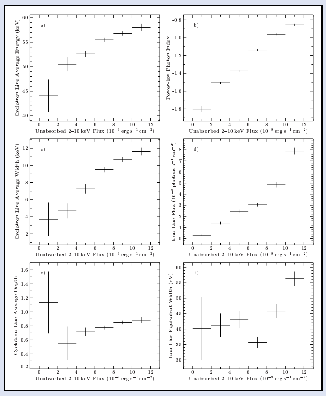
- Twenty accreting X-ray pulsars have been identified that exhibit cyclotron line features.
- Infalling supersonic material is dominated either by radiation pressure at high luminosities or Coulomb interactions at lower luminosities before settling onto the neutron star surface.
- GX 304−1 is an accreting neutron star exhibiting a teraGauss magnetic field in a high mass X-ray binary system with its companion B2Vne star, V850 Cen (Mason et al. 1978, Reig et al. 1997).
- GX 304−1 began a series of regularly spaced outbursts in late 2009. *RXTE* observed three of these in 2010, plus a fourth in May 2011, before the end of the mission.
- Yamamoto et al. (2011) discovered a CRSF at ~54 keV during the 2010 August outburst, and they suggested a possible positive correlation with flux.
- This correlation has been confirmed with recent *INTEGRAL* results by Klochkov et al. (2012) and Malacaria et al. (2015).
- To date, five accreting X-ray pulsars are known to have correlations of the fundamental cyclotron line energy with luminosity (V 0332+53 and 4U 0115+63, Her X-1 and A0535+26). GX 304−1 is the fifth (Klochkov et al. 2012).
- Other spectral components, such as the power law index (e.g., Malacaria et al. 2015) and iron line flux, have been seen to vary with accretion rate as expressed by the X-ray flux.

Data Selection and HEXTE Background

- We used 3−−60 keV PCU2 data, with responses generated for the specific observation day using PCARSP.
- We used 20−−100 keV HEXTE data from both clusters.
- **Due to rocking mechanism failures in the latter stages of the *RXTE* mission, HEXTE cluster A was continuously pointed on-source and cluster B was continuously pointed 1.5° off-source to collect background data for all observations.**
- **The background spectrum for cluster A was generated from that of cluster B using HEXTEBACKEST.**
- **Four narrow Gaussians with fixed energies at 30.17, 39.04, 53.0, and 66.64 keV, representing corrections to the HEXTEBACKEST estimated fluxes of four major HEXTE background lines were included in the modeling.**
- **The 30 keV and 67 keV lines are the strongest in the HEXTE background.**
- While the lines at 39 keV and 53 keV are of lesser strength, they may affect the measurement of the energy of the known cyclotron line at ~50-55 keV (Yamamoto et al. 2011), and were thus included in the fitting procedure.

The XSPEC model was: F(E)=Recor*Const*TBnew*(Powerlaw*Highecut*Gauabs + Gauss($Fe_{K\alpha}$) + Gauss($Fe_{K\beta}$)) + Sys where Sys denotes addition of Gaussian lines for HEXTE background modeling and PCU2 systematics at 3.88 keV.





The leftmost plot shows: **a)** a typical PCU2/HEXTE-A counts histogram plus best fit model covering 3−200 keV, **b)** the ratio of data to model with the best fit cyclotron line depth set to zero showing the response of both PCU2 and HEXTE-A to the line, **c)** the ratio of the data to the model with the best fit 4 HEXTE background lines set to zero flux, and **d)** the ratio for the best fit. The rightmost two column plots show variance-weighted spectral parameters versus flux. The cyclotron line parameters: energy **a)**, width **c)**, and depth **e)** are in one column and the photon index **b)**, iron line flux **d)**, and iron line equivalent width **f)** are in the other.

Scaling Laws of CRSF Properties in the Coulomb Braking Regime

Table 1: Fitting formulas for the CRSF centre energy, $E_{\rm cyc}$, width W, and line optical depth τ_1 as a function of X-ray flux $F_{\rm x}$ in the Coulomb braking regime, assuming the magnetospheric radius $R_{\rm m} \sim M^{-x}$

Formula	$x_{\rm d} = 2/7$			$x_{\rm s} = 2/11$		
$E_{\rm cyc}(F_{\rm x}) = K_{\rm E} e^{-K_1 F_{\rm x}^{-\alpha}}$	$\alpha_{\rm d} = 15/28$	$K_{\rm E} = 63.3 \pm 1.14$	$K_1 = 0.38 \pm 0.04$	$\alpha_{\rm s} = 27/44$	$K_{\rm E} = 61.67 \pm 1.10$	$K_1 = 0.35 \pm 0.04$
$W(F_{\rm x}) = K_2 E_{\rm cyc}^{1/3}(F_{\rm x}) F_{\rm x}^{\beta}$	$\beta_{\rm d} = 45/112$		$K_2 = 1.09 \pm 0.05$	$\beta_{\rm s} = 81/176$		$K_2 = 0.98 \pm 0.03$
$\tau_1(F_{\rm x}) = K_3 - \ln\left(E_{\rm cyc}^{2/3}(F_{\rm x}) F_{\rm x}^{-\gamma}\right)$	$\gamma_{\rm d} = 5/16$		$K_3 = 2.85 \pm 0.01$	$\gamma_{\rm s} = 63/176$		$K_3 = 2.76 \pm 0.02$

Two characteristic scales determine the physics of the cyclotron line formation in the Coulomb braking regime: the stopping length of infalling protons, scaling as $l_* \propto 1/(n_e \sigma_T)$, and the width of the cyclotron resonance layer, $\Delta r_{\rm res} \sim R_{\rm NS}\beta_T/3$, where $\beta_T = \sqrt{kT/m_e c^2}$ is the thermal velocity of electrons. With $kT_{\rm e} \sim 10$ keV, $\Delta r_{\rm res} \propto 3 \times 10^4$ cm can be of the order of the height of the accretion mound. Therefore, the fractional change in electron density with accretion rate, $\Delta n_{\rm e}/n_{\rm e} \simeq \Delta\dot{M}/\dot{M}$, would lead to the corresponding change in l_* and hence in the location of the cyclotron line formation region above the NS surface and its properties. Furthermore, the fractional change in the line energy, $\Delta E_{\rm cyc}/E_{\rm cyc}$, can be expressed as a function of $\Delta\dot{M}/\dot{M}$ or $\Delta F_{\rm x}/F_{\rm x}$, where $F_{\rm x}$ is the observed X-ray flux. Noticing that the temperature scaling with $\dot{M}$ can be found from the relation $T^4 A \propto \dot{M}$ (A is the polar cap area), the electron density can be related to the mass accretion rate as $n_e \propto \dot{M}^{\alpha}$, where the index α depends on the assumed scaling of the magnetospheric size on $\dot{M}$. Passing to differentials and integrating yields the formula for $E_{\rm cyc}(F_{\rm x})$ given in Table 1.

The relative width of the absorption line produced due to resonance scattering of photons in the strong magnetic field of the neutron star, $W/E_{\rm cyc}$, depends on the number of scatterings a given photon experiences before leaving the line formation region, $N_{\rm sc}$, and the fractional change in energy during each scattering, $(\Delta E/E)_1 \propto \beta_T$. As the motion of electrons in the strong magnetic field is essentially one-dimensional, $W/E_{\rm cyc} \propto \sqrt{N_{\rm sc}} \times (\Delta E/E)_1 \propto \sqrt{N_{\rm sc} T}$, which is familiar for thermal Comptonization. The ratio of the line center flux to the nearby continuum flux, $r = F_1/F_{\rm c}$, is also sensitive solely to the number of scatterings, since the true absorption coefficient in the continuum due to thermal bremsstrahlung is much smaller that the scattering coefficient, and can be neglected. Therefore, assuming for simplicity a plane-parallel isothermal atmosphere, we find $r \sim 1/\sqrt{N_{\rm sc}}$ (see e.g. Ivanov 1969).

The number of scatterings in the cyclotron resonant layer can be expressed through the layer's optical depth,$\tau_{\rm res}$ as, $N_{\rm sc} \propto \tau_{\rm res} \propto n_{\rm e}$ (e.g. Lyutikov and Gavriil, 2006), which yields the scalings $W \propto E_{\rm cyc}\sqrt{n_{\rm e} T}$ and $r \propto 1/\sqrt{n_{\rm e}}$ and corresponding dependences on $F_{\rm x}$ presented in Table 1. The ratio r can be also expressed in terms of the line "optical depth" τ_1, defined by the relation $r \equiv e^{-\tau_1}$. **For details see Rothschild et al. (soon to be submitted to MNRAS).**

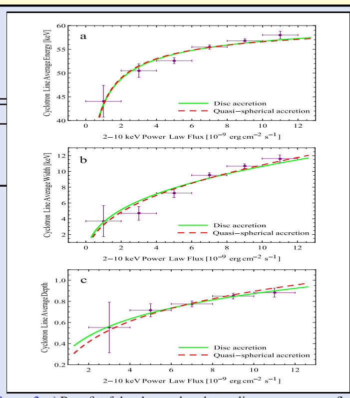


FIGURE 3: **a)** Best-fit of the observed cyclotron line energy versus flux ($E_{\rm cyc} - F_{\rm x}$) dependence for two possible regimes of accretion in GX 304-1, disc or settling subsonic, as given in Table 1, shown by solid gray line and black dashed line, respectively; **b)** The best-fit for the observed cyclotron line width versus flux ($W - F_{\rm x}$) dependence for the two accretion regimes, as given in Table 1; and **c)** The best-fit of the observed cyclotron line depth ($\tau_1 - F_{\rm x}$) dependence for the two accretion regimes, as given in Table 1.

Summary and Conclusions

We have measured the spectral parameters for 69 separate *RXTE* observations of three outbursts of GX 304−1 in 2010 and 2011 utilizing a very successful background estimation technique for generating HEXTE-A background estimates from the observed HEXTE-B background measurements. This has resulted in the discovery of a positive correlation of cyclotron line parameters with flux (luminosity) that flattens at higher fluxes. Properties of the CRSF resonant region above NS polar caps in Coulomb braking regime are shown to fit the correlations with flux very well. The power law index and the iron line flux are also positively correlated with flux, albeit without a flattening.

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