

Multiple Cyclotron Lines in the Spectrum of 4U 0115+63

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Abstract. We report phase resolved spectroscopy of the transient accreting pulsar, 4U 0115+63. For the first time, more than two cyclotron resonance scattering features are detected in the spectrum of an X-ray pulsar. The shape of the fundamental line appears to be complex, and this is in agreement with predictions of Monte-Carlo models. As in other pulsars, the line energies and optical depths are strong functions of pulse phase. One possible model for this is an offset of the dipole of the neutron star magnetic field.

I INTRODUCTION

4U 0115+63 is a transient accreting X-ray pulsar in an eccentric 24 day orbit [1] with an O9e star [10]. A cyclotron resonance scattering feature (CRSF) was first noted near 20 keV by Wheaton, *et al.* (1979) with the UCSD/MIT hard X-ray (10-100 keV) experiment aboard *HEAO-1*. White, Swank & Holt (1983) analyzed concurrent data from the lower energy (2-50 keV) *HEAO-1/A2* experiment and found an additional feature at ~ 12 keV, making 4U 0115+63 the first pulsar with two cyclotron line harmonics.

We discuss here phase-resolved spectra derived from an observation of the 1999 March outburst [13,3] obtained with the *Rossi X-Ray Timing Explorer (RXTE)*. First results of this work are detailed in Heindl *et al.* (1999). *BeppoSAX* has also made detailed observations of this outburst [8,9].

II OBSERVATIONS AND ANALYSIS

Observations were made with the Proportional Counter Array (PCA) [5] and High Energy X-ray Timing Experiment (HEXTE) [7] on board *RXTE*. The PCA is a set of 5 Xenon proportional counters sensitive in the energy range 2–60 keV

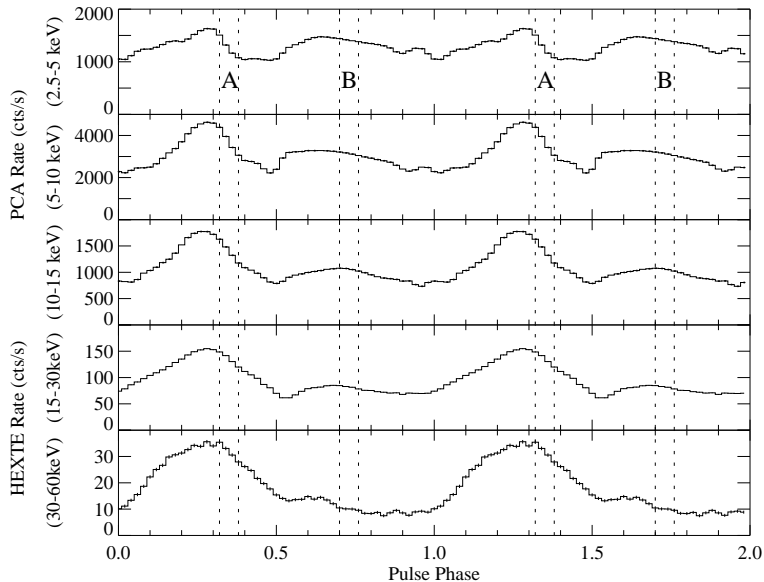


FIGURE 1. The folded light curve (or “pulse profile”) of 4U 0115+63 in five energy bands. We report detailed spectral analyses in phase ranges A and B which are indicated by the dashed lines.

with a total effective area of $\sim 7000 \text{ cm}^2$. HEXTE consists of two arrays of 4 NaI(Tl)/CsI(Na) phoswich scintillation counters (15-250 keV) totaling $\sim 1600 \text{ cm}^2$. The HEXTE alternates between source and background fields in order to measure the background. The PCA and HEXTE fields of view are collimated to the same 1° full width half maximum (FWHM) region.

We performed four long pointings (duration ~ 15 -35 ks to search for CRSFs. The second observation, on 1999 March 11.87-12.32, spanned periastron passage at March 11.95 ([1]) and preceded the outburst maximum by about 2 days. The results presented here are from this observation.

The spectrum of 4U 0115+63 varies significantly with neutron star rotation phase, making fits to the average spectrum difficult to interpret. To avoid this problem, we accumulated spectra as a function of pulse phase. Figure 1 shows the folded light curve in 5 energy bands. The pulse is double peaked at low energies, but the second peak nearly disappears at high energy. Two phase bands, “A” and “B”, which we selected for detailed analysis, are indicated. Our spectral fitting process consists of fitting the joint PCA/HEXTE spectra to various heuristic models (see Kreykenbohm, *et al.* 1998) which have been successful in fitting pulsars with no cyclotron lines. When none of these models can adequately describe the spectrum, and line-like residuals are present, we add Gaussian absorption lines to the spectrum as required. For a detailed description of our analysis technique, see Heindl, *et al.* (1999).

Figure 2 shows the resulting best fit spectra for phases A and B. Both fits have a Fermi-Dirac cutoff powerlaw continuum, a low energy excess in the form of a black body with $kT \sim 0.4 \text{ keV}$, *no* FeK line, and multiple cyclotron lines. In phase A, the falling edge of the main pulse, five cyclotron lines are required, while in phase B,

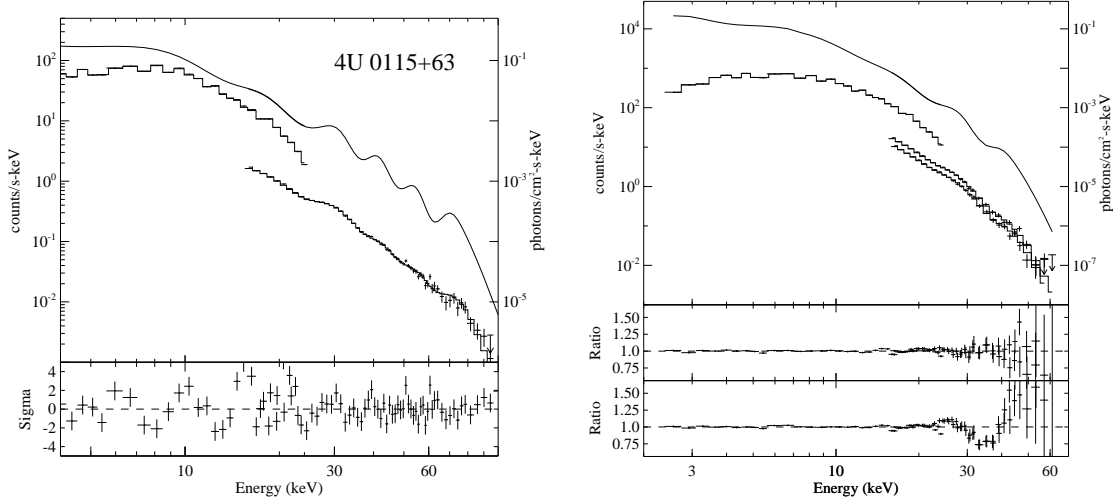


FIGURE 2. Best fit spectra to (left) phase A and (right) phase B. The top panel shows the inferred incident spectrum (smooth curve), the measured count spectra (data points), and the model count spectra (histograms). The bottom panels show residuals. For phase B, residuals fits with three (middle) and two (bottom) cyclotron lines.

the fall of the second pulse, only three lines are necessary. Figure 3 illustrates how we determine how many lines are present. The five panels show the residuals to phase A fits with increasing numbers of lines. With fewer than five lines, significant residuals are present. These residuals follow the pattern of a dip at the energy of the first missing line and a gross underprediction of the continuum at high energies. The fit continuum tends to conform to the low side of the missing line, because the statistics are rapidly decreasing with energy. The too steeply falling continuum can then never recover the high energy data. In phase A, adding five harmonics significantly improves the fit, while a sixth is not statistically required.

III RESULTS AND DISCUSSION

Table 1 lists the best fit cyclotron line parameters. Two interesting phenomena are apparent from these results. First, within the individual phases, the lines are not harmonically spaced. And, second, the line energies vary significantly with pulse phase.

A harmonic relation (with small modifications due to relativistic effects) between line energies is expected in simple Landau theory. However, models of cyclotron line formation (e.g. Isenberg, Lamb, & Wang 1998) predict that the fundamental line shape can be quite complex, even having wings resembling *emission* features. On the other hand, the higher harmonics should have relatively simple line shapes. Thus, it may be that our simple Gaussian absorption does not give an accurate measure of the fundamental line energy. Evidence for this appears in the residuals near 10–15 keV (see Fig. 3), which are the most significant remaining deviations in

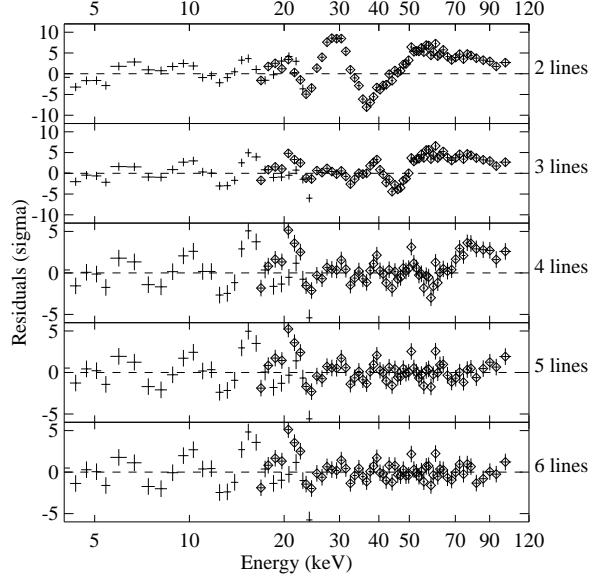


FIGURE 3. Residuals to fits to the phase A spectrum with different numbers of cyclotron line harmonics. Five lines are required to adequately fit the data.

our best fit. Furthermore the third and higher harmonics’ energies are consistent with integer multiples of *half* of the second harmonic energy. Thus it seems likely that *half* of the second harmonic energy gives a more accurate measure of the magnetic field. In the case of phase A, this is $B = 1.3 \times 10^{12}$ G, assuming a gravitational redshift of 0.3 to the neutron star surface.

Figure 4 shows the HEXTE flux and the ~ 20 keV line energy and optical depth as a function of pulse phase. These parameters were determined from the HEXTE data alone in 20 phase bins. The second harmonic line was not required in the HEXTE data *alone* at phases greater than 0.7. Both the line energy and optical depth are maximal not at the pulse peak, but on the falling edge of the main pulse. The line energy varies by $\sim 20\%$. This behavior is also seen in Cen X-3 [4]. In

TABLE 1. Best fit cyclotron line parameters from the two phase bins shown in Fig. 1.

Harmonic	Phase A			Phase B		
	Energy (keV)	Width ^a (keV)	Optical Depth	Energy (keV)	Width ^a (keV)	Optical Depth
1 ^b	$13.35^{+0.08}_{-0.06}$	$3.29^{+0.13}_{-0.07}$	$1.17^{+0.06}_{-0.04}$	$12.40^{+0.65}_{-0.35}$	$3.3^{+0.19}_{-0.4}$	$0.72^{+0.10}_{-0.17}$
2	23.7 ± 0.1	$5.43^{+0.18}_{-0.27}$	$2.68^{+0.05}_{-0.07}$	$21.45^{+0.25}_{-0.38}$	$4.5^{+0.7}_{-0.9}$	$1.24^{+0.04}_{-0.06}$
3	$36.4^{+0.4}_{-0.5}$	$4.3^{+0.4}_{-0.6}$	$2.41^{+0.11}_{-0.13}$	$33.56^{+0.70}_{-0.90}$	$3.8^{+1.5}_{-0.9}$	$1.01^{+0.13}_{-0.14}$
4	$47.8^{+0.4}_{-0.7}$	$5^{+\infty}_{-1.2}$	2.3 ± 0.2	–	–	–
5	61.7 ± 1.1	<i>fixed</i>	1.8 ± 0.3	–	–	–

^{a)} One standard deviation of the Gaussian optical depth profile

^{b)} also called the “fundamental”.

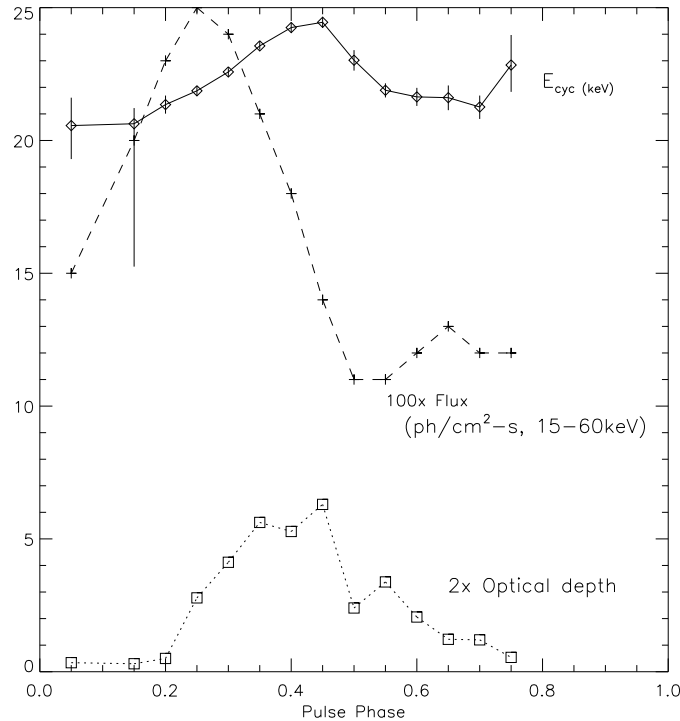


FIGURE 4. As a function of pulse phase, the energy (top) and depth (bottom) of the ~ 20 keV cyclotron line. Also plotted is the flux in the HEXTE band.

Cen X-3, Burderi et al. (2000) have modeled the variation of the line energy as due to an offset of the magnetic dipole moment from the center of the neutron star, and this may also be the case in 4U 0115+63.

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