THE ASTROPHYSICAL JOURNAL, 375:L49–L52, 1991 July 10

CYCLOTRON LINE FEATURES IN THE SPECTRUM OF THE TRANSIENT X-RAY PULSAR X0115+634

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Received 1990 November 26; accepted 1991 April 25

ABSTRACT

An outburst of the transient X-ray pulsar X0115+634 was detected with the All Sky Monitor (ASM) on board *Ginga* on 1990 February 5. Follow-up observations with the large-area proportional counters (LACs) revealed complex changes in the energy spectrum which depend on the phase of the 3.6 s pulsation. We find that characteristic structures in the spectra above 10 keV can be best interpreted as two dips at ~ 12 and ~ 23 keV, although not at all phases. The center energies of the two dips are consistent with the harmonic relation of 1:2, showing phase-dependent $\pm 10\%$ variations with pulse phase. The results strongly suggest that the structures in the spectra are due to cyclotron resonant scattering and the two apparent absorption lines are ascribed to the fundamental and second harmonics. This indicates a magnetic field strength on the neutron star surface of $\sim 1 \times 10^{12}$ G. Equivalent widths of the second harmonic line are about 2 times larger than those of the first harmonic line, depending on the pulse phase.

Subject headings: line identifications — pulsars — stars: magnetic — X-rays: binaries — X-rays: sources — X-rays: spectra

1. INTRODUCTION

A cyclotron line feature in an X-ray pulsar spectrum was first discovered from Her X-1 (Trümper et al. 1978). Whether this feature was due to an emission line at ~ 52 keV or to absorption at ~ 38 keV was unresolved (Voges et al. 1982; Soong et al. 1990). This feature of Her X-1 was studied again with the large area proportional counters (LACs) on board *Ginga* (Mihara et al. 1990), and similar features were discovered recently in the spectra of 4U 1538−52 (Clark et al. 1990) and X0331+53 (Makishima et al. 1990b) from *Ginga* observations. It was shown that these features, including that in Her X-1, can be consistently explained in terms of an absorption line rather than an emission line (Clark et al. 1990; Makishima et al. 1990b; Mihara et al. 1990).

With regard to X0115+634, Wheaton et al. (1979) reported the detection of an absorption line at ~ 20 keV in the energy spectrum of the source from an *HEAO 1* A-4 observation. From *HEAO 1* A-2 observations of this source, White, Swank, & Holt (1983) later reported that two line features were present at ~ 11.5 and 23 keV.

We describe here cyclotron line features observed with *Ginga* in the spectra of the X-ray binary pulsar X0115+634. The X-ray source X0115+634 is a recurrent transient X-ray pulsar from which eight outbursts have so far been observed between 1969 and 1987 at roughly 3 yr intervals (Tsunemi & Kitamoto 1988; Whitlock, Roussel-Dupré, & Priedhorsky 1989). A 3.6 s pulsation was discovered in the 1978 outburst (Cominsky et al. 1978), allowing the determination of an orbital period of 24.3 days, an eccentricity $e = 0.34$, and other orbital elements (Rappaport et al. 1978).

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2. OBSERVATIONS

An outburst of X0115+634 was detected with the All Sky Monitor (ASM; Tsunemi et al. 1989) aboard the *Ginga* satellite on 1990 February 5 at an intensity of ~ 100 mCrab flux units (Makino & The *Ginga* Team 1990). After the discovery of the outburst, the source was observed with the large area proportional counters (Turner et al. 1989) on board *Ginga* on three occasions: 1990 February 9, 1990 February 11, and 1990 February 12. The observations were made with the MPC-2 high bit-rate modes, that is, 48 pulse-height channels with 62.5 ms time resolution, covering the energy range 1.5–37 keV in the first observation and 1.5–60 keV in the latter two. The X-ray flux was about 400 mCrab on the average during the three observations. The average luminosity in the observed energy range was approximately 3×10^{37} ergs s^{-1} for the source distance of 3.5 kpc (White et al. 1983).

Apparent heliocentric pulse periods were measured to be 3.6144 ± 0.0001 s at MJD 47,931.917, 3.6148 ± 0.0002 s at MJD 47,933.874, and 3.615 ± 0.001 s at MJD 47,934.769. When the data are folded modulo these pulse periods, the pulse profiles show a double-peak structure with a sharp main peak and a broad secondary peak.

3. RESULTS OF SPECTRAL ANALYSIS

We show in Figure 1 (*top panel*) the phase-averaged pulse-height spectrum of X0115+634 observed with the LACs on 1990 February 9. This spectrum is fitted, as a first step, with a

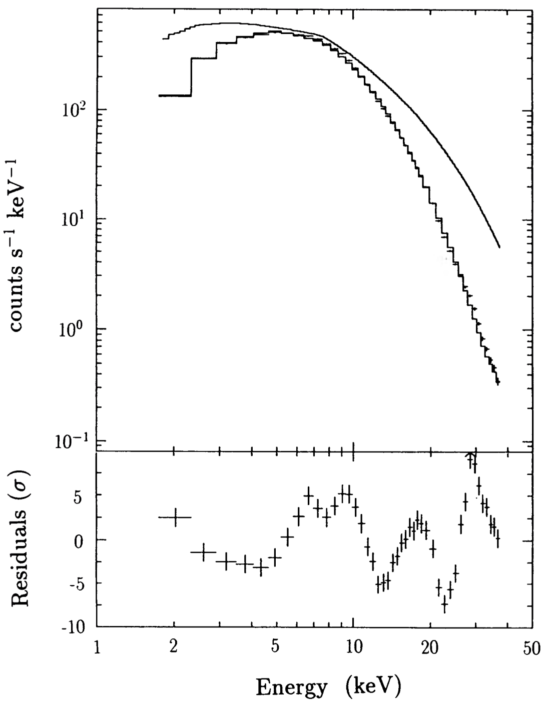

FIG. 1.—Phase-averaged pulse-height spectrum (counts keV^{-1} s^{-1}) of X0115+634 (*plus signs*) observed with the LACs aboard *Ginga* (*top panel*). The histogram shows the best-fit model function of eq. (1) after convolution with the detector response. The solid line above the histogram is the incident photon spectrum (photons keV^{-1} s^{-1}) inferred from the best-fit parameters. Deviations of the pulse-height spectrum from the best-fit model function are shown in the bottom panel. Systematic structure is clear above 10 keV, in addition to a peak around 6–7 keV due to an iron line.

model comprising a power law of photon index α, modified at energies above a high-energy cutoff E_c by an exponential function with folding energy E_f and at low energies by photoelectric absorption due to intervening cold matter of column density N_H with cosmic abundances

$$f_0(E) = AE^{-\alpha} \exp\left[-\sigma N_H - H(E)\right] ,$$

$$H(E) = \begin{cases} 0 & \text{for } E \le E_c \, , \\ \dfrac{E - E_c}{E_f} & \text{for } E \ge E_c \, . \end{cases} \tag{1}$$

The model spectrum given by equation (1) provides a qualitative approximation to the observed spectrum as shown by a histogram in Figure 1, with best-fit parameter values of $\alpha = 0.46$, $E_c = 7.4$ keV, $E_f = 8.0$ keV, and $N_H = 1.2 \times 10^{22}$ cm^{-2}. These are consistent with previous results (Rose et al. 1979; White et al. 1983). However, this fit is not formally acceptable with an extremely large value of reduced χ^2 of 16.3 (40 degrees of freedom). From the residuals of the model fitting (see Fig. 2, *bottom panel*), it is evident that the observed spectrum has systematic structure at energies above 10 keV in addition to a faint peak around 6–7 keV attributed to an iron line.

The pulse-height spectrum was sorted into eight pulse phases of equal intervals, with the phase-zero reference taken to be the time of minimum intensity of the pulse. In Figure 2 we show the spectra in the form of the ratio to the best-fit model of smooth continuum, in which parameters of the model spectrum were derived from the fit by equation (2), to each spectrum, the data between 11 and 28 keV being discarded. It is clear that the spectrum shows strongly phase-dependent variation. The most prominent feature is the presence of two dips at $\sim$12 and $\sim$23 keV in most of the pulse-phase intervals (note that the faint peak at 6–7 keV attributed to iron emission lines is visible at all phases). This encourages us to perform further fitting by including two absorption lines.

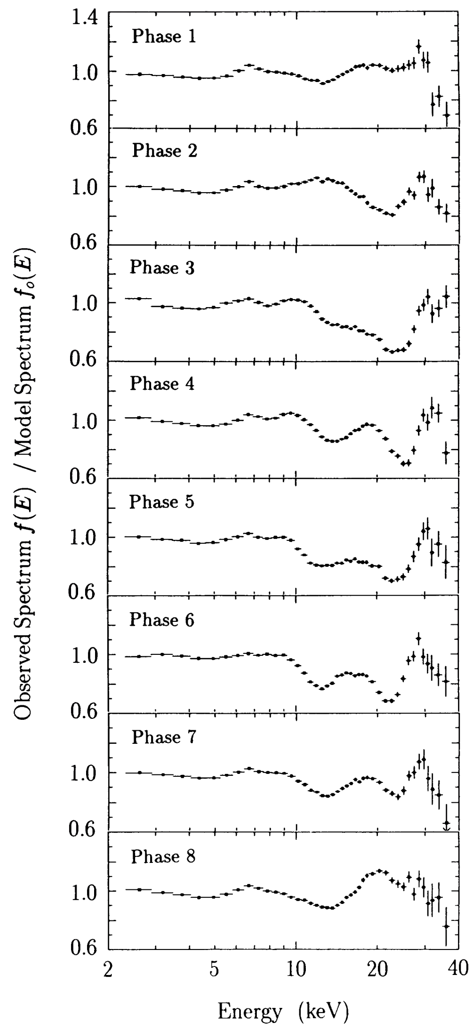

FIG. 2.—Ratios of the observed spectrum $f(E)$ of X0115+634 to the best-fit model spectrum $f_0(E)$ are shown for the eight pulse phases. The model is a power law with low-energy absorption and high-energy cutoff of eq. (1), and the parameters of the model are adopted from the fit to the energy spectrum of each phase.

As a second step, we performed the fits for the eight phase-resolved spectra with a model function involving two absorption lines of a Lorentzian-type form $L(E)$ and an iron emission line at 6.4 keV of a Gaussian form $G(E)$:

$$f_1(E) = AE^{-\alpha} \exp\left[-\sigma N_H - H(E) - L(E)\right] + G(E) \, ,$$

$$L(E) = \frac{\tau_1 W_1^2 (E/E_1)^2}{(E - E_1)^2 + W_1^2} + \frac{\tau_2 W_2^2 (E/E_2)^2}{(E - E_2)^2 + W_2^2} \, , \tag{2}$$

where E_i, W_i, and τ_i are the energy, the width, and the optical depth of the absorption line, respectively, and the subscript 1 denotes the first absorption line and 2 the second. The function $L(E)$, representing an absorption-line measure, resembles the cross section of cyclotron resonant scattering (Herold 1979; Daugherty & Harding 1986). In our fits the energy and width

TABLE 1

PARAMETERS OF THE TRIAL FUNCTION (eq. [2]) FITTED TO THE PULSE-HEIGHT SPECTRA[a]

Parameter	Phase 1	Phase 2	Phase 3	Phase 4	Phase 5	Phase 6	Phase 7	Phase 8
				Continuum				
Flux[b]	1.64 ± 0.01	2.21 ± 0.01	2.92 ± 0.01	2.25 ± 0.01	1.84 ± 0.01	2.17 ± 0.01	1.96 ± 0.01	1.71 ± 0.01
α	0.45 ± 0.07	0.46 ± 0.04	0.11 ± 0.07	0.25 ± 0.05	0.32 ± 0.03	0.45 ± 0.04	0.47 ± 0.03	0.46 ± 0.04
E_c (keV)	8.5 ± 0.4	8.1 ± 0.6	9.2 ± 0.3	9.0 ± 0.4	8.5 ± 0.3	8.0 ± 0.4	7.9 ± 0.3	7.1 ± 0.5
E_f (keV)	9.9 ± 0.5	10.6 ± 0.8	8.8 ± 0.4	8.3 ± 0.5	8.5 ± 0.4	8.2 ± 0.4	8.6 ± 0.4	12.3 ± 1.8
				First Absorption Line				
τ_1	0.23 ± 0.03	...	0.37 ± 0.03	0.31 ± 0.05	0.37 ± 0.03	0.31 ± 0.03	0.27 ± 0.03	0.36 ± 0.07
E_1 (keV)	10.6 ± 0.5	...	12.5 ± 0.5	12.9 ± 0.4	11.4 ± 0.3	11.8 ± 0.2	11.9 ± 0.2	11.9 ± 0.3
W_1 (keV)	4.0 ± 0.9	...	4.6 ± 0.8	3.3 ± 0.8	3.5 ± 0.4	2.1 ± 0.4	3.3 ± 0.5	4.5 ± 0.9
EW[c] (keV)	2.3 ± 1.0	...	3.4 ± 0.8	2.3 ± 1.0	2.9 ± 0.7	1.6 ± 0.5	2.1 ± 0.7	4.2 ± 2.5
				Second Absorption Line				
τ_2	...	0.37 ± 0.07	0.82 ± 0.07	0.57 ± 0.10	0.58 ± 0.07	0.47 ± 0.05	0.37 ± 0.08	...
E_2 (keV)	...	19.7 ± 0.5	22.3 ± 0.4	24.4 ± 0.3	21.8 ± 0.4	21.4 ± 0.3	23.0 ± 0.5	...
W_2 (keV)	...	5.8 ± 1.6	7.2 ± 0.7	3.7 ± 1.1	6.5 ± 0.7	3.1 ± 0.7	5.3 ± 1.0	...
EW[c] (keV)	...	4.5 ± 2.1	9.8 ± 1.5	4.7 ± 2.1	6.9 ± 1.8	3.3 ± 1.1	4.1 ± 1.8	...
				Iron Line				
EW[d] (keV)	0.13 ± 0.04	0.11 ± 0.04	0.12 ± 0.03	0.08 ± 0.03	0.11 ± 0.03	0.10 ± 0.04	0.10 ± 0.03	0.10 ± 0.04
χ^2_ν [e]	0.77	0.89	1.21	0.64	1.04	1.56	0.68	1.05

[a] All quoted errors represent 90% confidence limits for a single parameter.

[b] Energy flux in the range 2–30 keV in units of 10^{-8} ergs s^{-1} cm^{-2}.

[c] Measures of equivalent width are computed using the best-fit parameters α, E_c, and E_f for the continuum and τ_i, E_i, and W_i ($i = 1, 2$) for the absorption feature.

[d] Equivalent width of iron line derived from the fit by fixing central energy and line width to 6.4 and 0.2 keV, respectively.

[e] Reduced χ^2 values for 27 degrees of freedom.

of an iron line were fixed at 6.4 and 0.2 keV, respectively. The fitting of the eight phase-resolved spectra involved 12 free parameters of the model function in equation (2). The resulting best-fit parameters are summarized in Table 1, and an example of the fits is shown in Figure 3 for the spectrum in pulse phase 6.

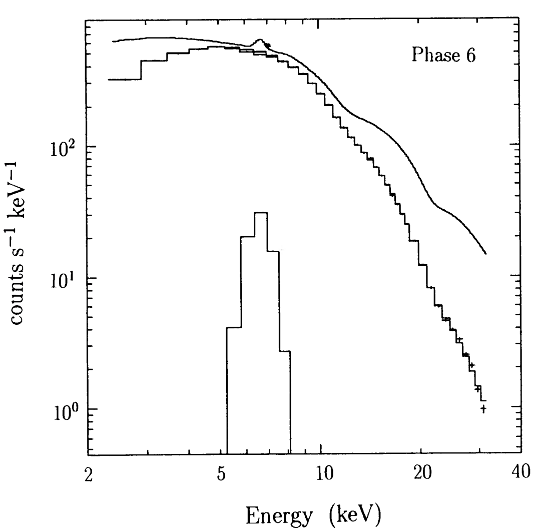

FIG. 3.—Pulse-height spectrum (counts keV^{-1} s^{-1}) of X0115+634 at phase 6 (*plus signs*) observed with the LACs aboard *Ginga*. The histogram shows the best-fit model function of eq. (2) after convolution with the detector response. The solid line above the histogram is the incident photon spectrum (photons keV^{-1} s^{-1}) inferred from the best-fit parameters.

Two significant absorption lines were obtained for phases 3–7, whereas only the first was significant for phases 1 and 8 and only the second for phase 2. The energies of the dips, averaged over phases 3–7 (at which two dips have been significantly determined) are 12.1 ± 0.2 and 22.6 ± 0.4 keV, respectively. It is apparent from the fit that the center energies of these dips drift as much as ±10% with phase. The ratios of the two center energies are in the range between 1.8 and 1.9, and the average is 1.87 ± 0.05. The difference of these values from 2, the value expected from the harmonic relation between the two resonant lines, is marginally significant on the basis of single-parameter 90% confidence limits. However, the fitting with such a model as equation (2) is inevitably affected by the assumption made for the underlying continuum and is hence somewhat model-dependent. The slight difference of the value from 2 will be discussed later.

The correlation between the high-energy cutoff in continuum spectra and the cyclotron energy has been suggested for many pulsars (Tanaka 1986). It has been recently shown that the function $L(E)$ describes simultaneously the cyclotron absorption feature observed and the high-energy cutoff that is characteristic of X-ray pulsar spectra (Makishima et al. 1990a, b; Mihara et al. 1990). In the case of X0115+634, however, we need both the $L(E)$ and $H(E)$ terms to obtain acceptable fits for the spectra. This may be due to the fact that X0115+634 has an extremely flat spectrum at energies below 8 keV with a remarkably steep cutoff, whereas the equivalent widths of the absorption lines at 12 and 23 keV are relatively small.

From the features seen in Figure 2, one might think of the alternative interpretation that the observed structure is due to two peaks at ~ 10 and 20 keV. To examine this emission-line interpretation, we have performed the fit involving emission lines with a Gaussian form instead of the Lorentzian absorption lines of the function $L(E)$. The inclusion of two Gaussian lines does not give an acceptable fit for any of the eight phases. Instead, however, it is found that the inclusion of a third emission line near 30 keV gives acceptable fits for all phases with an accordingly steeper turnover. Such fits yield reduced χ^2 values comparable to the previous fits in Table 1. The energies of the three emission lines, however, do not keep the harmonic relation in any of the phases. Hence it would be more plausible to consider that the two dips are the fundamental structures.

4. DISCUSSION

We have found that the spectra of X0115+634 resolved into eight phases can be consistently interpreted by two absorption lines at ~ 12 and ~ 23 keV superposed on the portion above the cutoff energy where the continuum intensity decreases exponentially, thus qualitatively confirming the previous work by White et al. (1983). Our analysis, however, does not indicate the model proposed by them, in which the two lines were assumed to appear in absorption during the main pulse but in emission during the interpulse. Nevertheless, it is evident that the absorption feature changes with phase, and occasionally (at phases 1, 2, and 8) one of the expected two dips diminishes into insignificance.

We obtained in the present analysis a value of 1.87 for the ratio of the first and second absorption-line energies, which is slightly ($\sim 7\%$) different from 2 with marginal (2.6 σ) significance. The ratio of the first and second harmonic energies could be reduced by at most only about 1%, for the case where photons propagate perpendicular to the magnetic field line taking into account relativistic effects (Herold 1979; Daugherty & Harding 1986). One should notice, however, that the errors for the values in Table 1 are 90% confidence limits for a *single* parameter, whereas the determination of line energies is inevitably coupled with the assumption for the underlying continuum. To examine this problem in more detail, we performed fitting with equation (2) by fixing $E_2 = 2E_1$ for the spectra in phases 3–7 in which two absorption lines were significant. The results lead to acceptable fits with reduced χ^2 values 1.1–1.4 times larger than those in Table 1. The F-tests for the omission of one parameter (E_2) lead to the conclusion that the assumption $E_2 = 2E_1$ is allowable with probabilities greater than a few percent. Hence the two apparent absorption lines observed from X0115+634 are consistent with a harmonic relation of 1:2, and they can be interpreted as due to cyclotron resonant scattering in a strongly magnetized plasma and correspond to the fundamental and the second harmonic energies. Based on this interpretation, the fundamental resonance at 12.1 keV corresponds to a magnetic field strength of $1.04 \times 10^{12}(1 + z)$ G on the neutron star surface, where z is the gravitational redshift.

The equivalent width of the second harmonic line is found to be comparable to or larger than that of the fundamental line by a factor of about 2 (see Table 1). This property in the X-ray spectra of X0115+634 is similar to that observed from γ-ray burst spectra with *Ginga* (Murakami et al. 1988; Fenimore et al. 1988). It is notable that the properties of the first and second harmonic lines observed from the γ-ray burst spectra were qualitatively interpreted using numerical calculations based on the theory of radiation transfer in a strong magnetic field (Alexander & Mészáros 1989; Wang et al. 1989; Lamb et al. 1989).

It is worth noting that the central energy of the absorption dip in X0115+634 drifts from phase to phase as much as $\pm 10\%$, as seen in Table 1. Such an apparent phase dependence of the cyclotron line energy has already been reported for Her X-1 (Voges et al. 1982; Soong et al. 1990) and 4U 1538−52 (Clark et al. 1990). These phase-dependent changes may be due to the geometry of the site where the cyclotron resonant scattering takes place along the change of phase. A hint for such drift of dip energy has already been suggested by the calculations by Lamb et al. (1989), in which the central energy of apparent absorption dips varies as much as $\sim 10\%$, depending on the angle between the photon propagation direction and the magnetic field.

We thank Charles S. R. Day and Tahir Yaqoob for critical reading of the manuscript and useful comments.

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