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DISCOVERY OF A CYCLOTRON RESONANCE FEATURE AT 30 keV FROM THE TRANSIENT X-RAY PULSAR CEPHEUS X-4

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ABSTRACT

From *Ginga* observations of the transient X-ray pulsar Cep X-4, a spectral line feature attributable to electron cyclotron resonance was discovered at about 30 keV in the 1.2–37 keV X-ray spectrum. The detection, a fifth firm example of cyclotron resonance from X-ray pulsars, implies a surface magnetic field of about $2.6 \times 10^{12}(1 + z)$ G for this pulsar, where z is the gravitational redshift. Throughout the 66.25 s pulses, the cyclotron feature appears in absorption, with at most $\pm 5\%$ variation in the resonance center energy around the mean value of 30.5 ± 0.4 keV. The resonance profile depends significantly on the pulse phase in such a way that it is deepest on the decay slope of the leading peak of the double-peaked pulse profile.

Subject headings: stars: magnetic — stars: neutron — X-rays: binaries — X-rays: spectra

1. INTRODUCTION

Detection of X-ray spectral line features due to electron cyclotron resonance scattering, or cyclotron resonance scattering features (CRSFs), provides direct information on the surface magnetic field strengths of mass-accreting X-ray pulsars. Here we report on the discovery of a CRSF at about 30 keV in the transient X-ray pulsar Cep X-4.

The transient X-ray source Cep X-4 (GS 2138+56; possibly identical to 4U 2135+57), previously observed with *OSO 7* in 1973 (Ulmer et al. 1973; Markert et al. 1973), was rediscovered in a $\sim$100 millicrab outburst with the *Ginga* All Sky Monitor in 1988 March (Makino & *Ginga* team 1988a). Pointed observations made with the *Ginga* Large Area Proportional Counter (LAC; Turner et al. 1989) have revealed that it is an X-ray pulsar with a pulse period of 66.25 s (Makino & *Ginga* team 1988b).

X-ray timing results on Cep X-4 from these *Ginga* observations have been published as Koyama et al. (1990, hereafter Paper I), who showed that the orbital period of Cep X-4 is greater than 23 days and its projected orbital semimajor axis is $a_x \sin i > 9$ lt-sec. They argued that, although optical identification is yet to be made, Cep X-4 is most likely a Be pulsar (Corbet 1984, 1986), that is, a magnetized neutron star in an eccentric orbit around a Be-type binary companion; such a system very often becomes a recurrent transient X-ray source. Utilizing an empirical relation between pulse period and binary period of Be pulsars (Corbet 1986), they estimated the orbital period of Cep X-4 to be $\sim$100 days. The observed pulse period change was consistent with an orbital Doppler effect implied by this binary period and an assumed companion mass of greater than 10 $M_{\odot}$.

Furthermore, in Paper I presence of a CRSF was suggested at $\sim$31 keV in the X-ray spectrum. We have performed further analysis of the X-ray spectrum and confirmed this suggestion. We also study the cyclotron feature as a function of pulse phase and average X-ray luminosity.

2. OBSERVATIONS

The LAC was pointed at Cep X-4 on three occasions in 1988, April 3.91–4.28, 8.74–10.47, and 14.55–15.15 UT, achieving effective on-source exposure times of 1.0×10^4, 4.6×10^4, and 1.7×10^4 s, respectively. The 2–20 keV source intensity on these occasions was about 85, 70, and 45 millicrab, respectively. The LAC data were acquired in 48 spectral channels (MPC-1 and MPC-2 modes) covering an energy range of 1.2–37 keV, with a time resolution of either 0.5 or 2.0 s. These data sets are the same as used in Paper I. Further details of observation, including the source identification and the discovery of pulsation, are given in Paper I.

3. DATA ANALYSIS AND RESULTS

Figure 1 shows the 1.2–37 keV pulse-height spectrum of Cep X-4, averaged over the entire observation and over the 66.25 s pulse phase. It is essentially the same as Figure 5 of Paper I, which, however, had been truncated at 28 keV. The LAC spectra of Her X-1 (Mihara et al. 1990) and 4U 1538−52 (Clark et al. 1990), both exhibiting CRSFs, are also shown for comparison. Thus the Cep X-4 spectrum indeed exhibits a noticeable curvature change, or a broad concave feature, near 30 keV. The feature looks very similar to the CRSFs of Her X-1 (centered at $\sim$35 keV) and 4U 1538−52 (centered at $\sim$21 keV), suggesting that it is of the same origin. We also accumulated the spectra separately for the three observations and found that the feature is visible in all of them. However, caution is needed because a similar spectral feature could arise spuriously from instrumental effects due to Xe K-edge (at 35 keV) in the detector gas.

Experience with Her X-1 (Mihara et al. 1990), 4U 1538−52 (Clark et al. 1990), and 4U 0115+63 (Nagase et al. 1991) indicates that a real CRSF would show significant pulse-phase dependence in its depth and width. In order to see if this also holds for Cep X-4, we sorted the spectrum into eight pulse phases of equal length, in reference to the folded pulse profile

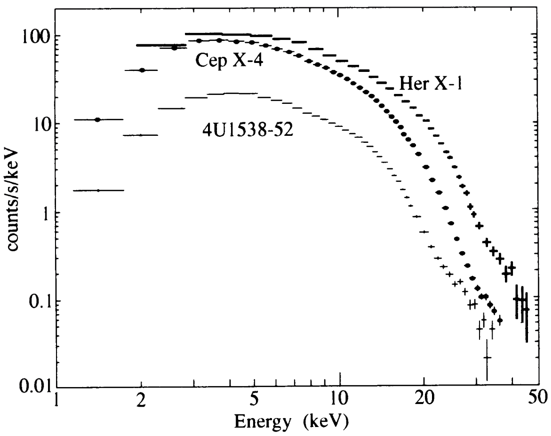

FIG. 1.—Pulse-height spectrum of Cep X-4 observed with the *Ginga* LAC, averaged over the entire observation. For comparison, pulse-phase-averaged spectra of Her X-1 (acquired with a reduced high voltage; Mihara et al. 1990) and 4U 1538−52 (Clark et al. 1990) are also shown. Instrumental response is not removed. Cyclotron resonance occurs at ~30, ~35, and ~21 keV for Cep X-4, Her X-1, and 4U 1538−52, respectively.

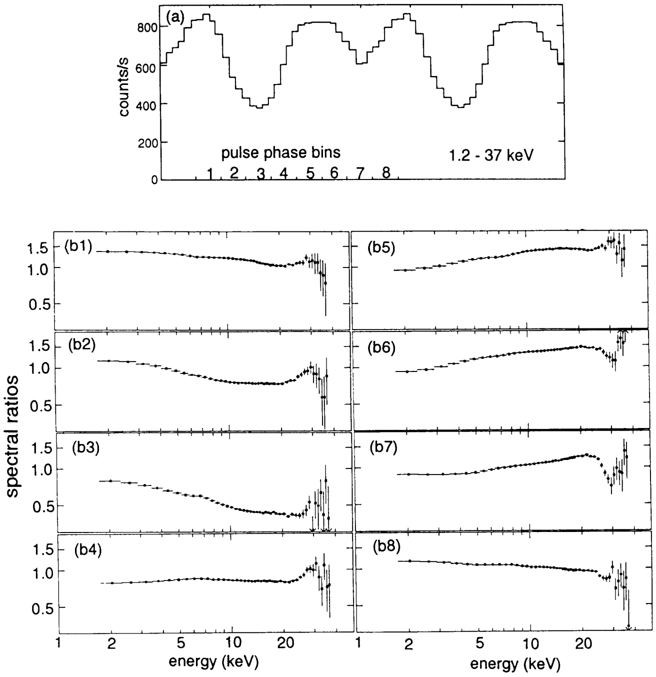

FIG. 2.—(*a*) The 1.2–37 keV pulse profile of Cep X-4 folded at 66.25 s. (*b1*)–(*b8*) Pulse-phase-resolved spectra of Cep X-4, corresponding to the pulse-phase bins 1–8 of panel (*a*), each normalized to the phase-averaged spectrum of Cep X-4 shown in Fig. 1.

(Fig. 3 of Paper I) which is reproduced here as Figure 2*a*. The data includes ~1100 cycles of the 66.25 s pulse. In Figure 2*b*, we present these pulse-phase-resolved spectra each normalized to the phase-averaged total spectrum of Cep X-4 (Fig. 1). In these ratios the suggested spectral feature has been resolved clearly and confirmed unambiguously; it appears as a conspicuous dip at ~30 keV in the ratios for phases 6 and 7, while it appears as a positive hump at similar energies for phases 2–5. An instrumental feature would never show such a sensitive dependence on the pulse phase. Similarly, the complex behavior of these ratios cannot be explained in terms of structures in the background spectrum. We are therefore convinced that the feature is real and interpret it as a CRSF, thus confirming the suggestion made in Paper I.

We fitted the spectrum first with the "exponential cutoff" model (White, Swank, & Holt 1983), that is, a power-law model continuum of the form $f(E) = IE^{-\alpha}$ multiplied for $E > E_c$ by a factor $\exp[-(E - E_c)/E_f]$. Here E is the X-ray energy, $f(E)$ is the photon flux, I is the normalization, α is the photon index, and E_c and E_f are cutoff parameters. To emphasize the hard X-ray region and to avoid the complication of Fe K-edge and K-line, we restricted the fit range to greater than 8.9 keV. The model failed to give acceptable fits to any of the pulse-phase-averaged and phase-resolved spectra of Cep X-4. Figure 3*a* shows the phase-averaged case, with $\chi^2/\nu = 16.6$ for $\nu = 28$. The data fall significantly short of the model at ~18 and ~30 keV, the former caused by the kink in the model at $E \sim E_c$ (Makishima et al. 1990a; Paper I). The latter structure is attributed to the CRSF. An improved model of the form

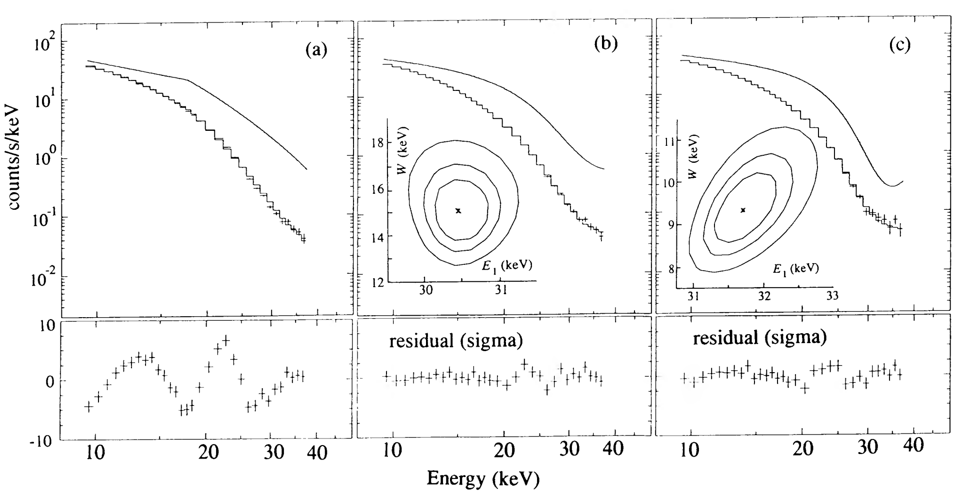

FIG. 3.—The 8.9–37 keV portion of pulse-height spectra of Cep X-4, fitted with two different model spectra. In top panel, upper smooth curve represents best-fit model in its incident form, while stepwise function shows same model convolved through detector response to be compared with raw data (*crosses*). Bottom panel shows fit residuals in units of standard deviation. (*a*) Pulse-phase-averaged spectrum fitted with exponential cutoff model. (*b*) Same spectrum fitted with "cyclotron scattering cutoff" model (*see text*). Inset shows 68%, 90%, and 99% confidence contours of fit on the E_1-W plane. (*c*) Same as (*b*), but for pulse phase 7 of Fig. 2 where the resonance feature is most prominent.

$f(E) = IE^{-\alpha}\{1 + \exp[(E - E_c)/E_f]\}^{-1}$, first introduced by Tanaka (1986), was also rejected, due to the 30 keV negative feature.

As an alternative model, we next tried the "power-law times cyclotron scattering cutoff" model (Tanaka 1986),

$$f(E) = IE^{-\alpha} \exp\left[-\frac{D(WE/E_1)^2}{(E - E_1)^2 + W^2}\right]. \quad (1)$$

Here the factor in exponential approximates the classical cross section for the cyclotron scattering, with E_1 the electron cyclotron energy, D the optical depth at the resonance, and W the resonance width. When $E_1 \ll 511$ keV, we have $E_1 = 11.6(B/10^{12}\text{ G})/(1 + z)$ keV where B is the rest-frame magnetic field and z is the gravitational redshift. This formula has successfully reproduced the overall hard X-ray spectra of Her X-1 (Mihara et al. 1990), 4U 1538−52 (Clark et al. 1990), and X0331+53 (Makishima et al. 1990a, b). Leaving I, α, D, E_1, and W free, we obtained acceptable fits to all the phase-averaged (Fig. 3*b*) and phase-resolved (e.g., Fig. 3*c*) spectra of Cep X-4. Numerical results are summarized in Table 1. The value of E_1 has turned out within a narrow ($\pm 5\%$) range of the mean value of ~ 30.5 keV. This means that E_1 is a well-defined quantity of this source, and we regard it as representing the surface field strength at the magnetic poles where the X-ray emission is thought to occur. The implied magnetic field intensity is about $2.6 \times 10^{12}(1 + z)$ G.

The scattering depth D and the resonance width W depend on the pulse phase in a rather complex manner. We first remark that the CRSF appears in *absorption* (i.e., $D > 0$) rather than in *emission* throughout the pulse phase. The largest D and the smallest W have been observed on the latter half of the first pulse peak (phase 6 and 7), implying that there the CRSF is most prominent (see Fig. 3*c*); actually the spectral ratios in Figure 2 exhibit the deepest dip at these phases. On the other hand, the CRSF is rather obscure across the pulse bottom, with small values of D; for these phases the CRSF generally appears as positive humps in Figure 2*b*, because the spectrum near E_1 is less attenuated in these phases than in the phase-averaged spectrum.

Since the CRSF appears as a broad feature near the upper end of the spectrum (Fig. 3), the value of E_1 systematically depends on the fit model by $\sim \pm 2$ keV. However, our fitting results are otherwise reliable. The LAC response over the entire 1.2–37 keV range has been calibrated within a typical error of 1% (Turner et al. 1989; Hayashida et al. 1989), which is taken into account in the spectral fitting. The background level is known to $\lesssim 1 \times 10^{-2}$ counts s^{-1} keV^{-1} (Hayashida et al. 1989), and amplitude of any residual background feature near 30 keV is even a small fraction of this uncertainty. Therefore data error at the highest energy region is dominated by photon-counting statistics rather than systematic uncertainties. Above the inferred resonance there exist ~ 6 data points, which adequately constrain the resonance parameters as demonstrated by the χ^2 contour maps on the E_1-W plane (insets to Figs. 3*b* and 3*c*). Finally the exclusion of less than 8.9 keV data points from the fitting is well justified, because the spectrum below 20 keV depends little on the pulse phase except for changes in continuum slope and iron line strength (Fig. 2*b*).

4. DISCUSSION

We have discovered a CRSF at about 30 keV in the spectrum of Cep X-4, which indicates a surface magnetic field intensity of $2.6 \times 10^{12}(1 + z)$ G. This provides the fifth firm detection of a CRSF from binary X-ray pulsars, following Her X-1 ($E_1 \sim 35$ keV; Voges et al. 1982; Mihara et al. 1990), 4U 0115+63 ($E_1 \sim 12$ keV; Wheaton et al. 1979; White et al. 1983; Nagase et al. 1991), 4U 1538−52 ($E_1 \sim 21$ keV; Clark et al. 1990), and X0331+53 ($E_1 \sim 28.5$ keV; Makishima et al. 1990b). In all these pulsars, the CRSF appears as a characteristic spectral dip superposed upon a steeply falling continuum, in agreement with theoretical calculations (e.g., Alexander & Mészáros 1991). The present discovery reinforces the suggestion (Makishima et al. 1990b; Mihara et al. 1990) that the CRSF is a common phenomenon among accretion-powered pulsars, and that the CRSF plays an essential role in the formation of prominent turnover in the X-ray continuum of these objects.

In Table 1, we find some hint of an increase in W and a slight decrease in E_1 as the source gets brighter. Although sta-

TABLE 1

RESULTS OF SPECTRAL FITTING TO PULSE-PHASE-AVERAGED AND PULSE-PHASE-RESOLVED SPECTRA OF CEP X-4, USING "POWER-LAW TIMES CYCLOTRON SCATTERING CUTOFF" MODEL[a]

Phase[b]	F_{9-37}[c]	α	D	E_1(keV)	W (keV)	χ^2/ν
Phase averaged:						
Total	180	0.91 ± 0.08	2.93 ± 0.10	30.5 ± 0.4	15.0 ± 1.4	0.80
Apr 3–4	227	0.58 ± 0.09	2.88 ± 0.11	30.2 ± 0.5	16.1 ± 1.8	0.69
Apr 8–10	190	0.58 ± 0.08	3.03 ± 0.11	30.6 ± 0.4	15.3 ± 1.5	0.67
Apr 14–15	120	0.69 ± 0.09	2.88 ± 0.18	31.0 ± 0.7	13.6 ± 1.9	0.56
Phase resolved:						
Phase 1	206	0.70 ± 0.02	2.65 ± 0.05	29.7 ± 0.4	20.1 ± 0.7	1.32
Phase 2	135	0.68 ± 0.02	2.57 ± 0.06	30.6 ± 0.4	18.6 ± 0.7	0.83
Phase 3	81	0.89 ± 0.02	2.48 ± 0.08	29.5 ± 0.4	13.5 ± 0.6	1.11
Phase 4	146	0.60 ± 0.02	2.52 ± 0.05	29.5 ± 0.4	17.5 ± 0.6	0.95
Phase 5	248	0.35 ± 0.03	2.92 ± 0.05	29.5 ± 0.4	16.8 ± 0.4	0.52
Phase 6	245	0.63 ± 0.06	3.20 ± 0.11	30.7 ± 0.5	11.4 ± 1.0	1.14
Phase 7	198	0.63 ± 0.06	4.08 ± 0.24	31.7 ± 0.6	9.3 ± 0.9	1.07
Phase 8	180	0.78 ± 0.03	3.16 ± 0.08	31.0 ± 0.5	13.8 ± 0.6	1.53

[a] See text. Quoted errors are single-parameter 90% confidence limits. Degree of freedom of the fit is $\nu = 27$.

[b] Definition of the pulse phase refers to Fig. 2*a*.

[c] Observed X-ray intensity (in counts s^{-1}) in the energy range 8.9–37 keV, for the 4000 cm^2 effective area.

tistically not significant in the present data alone, these effects are naturally expected from the following simple-minded picture. As the mass accretion rate increases, the accretion columns at the magnetic poles will become taller. Then the field intensity will exhibit a wider distribution over the emission region, leading to an increase in W, as well as a slight decrease in the average field intensity, hence in the value of E_1. Furthermore, a higher temperature of the emitting plasma implied by the higher accretion rate will contribute to the increase in W through enhanced thermal Doppler broadening.

The 2–20 keV luminosity of Cep X-4 on April 3 was $7 \times 10^{35} d^2$ ergs s^{-1}. Here d, the distance in kpc, is probably less than 5 considering the anti-Galactic-center direction and a relatively low absorption ($\sim 10^{22}$ cm^{-3}; Paper I) of Cep X-4. Therefore the luminosity of Cep X-4 was at most 2×10^{37} ergs s^{-1}. The outburst luminosities of 4U 0115+63 and X0331+53 have been estimated to be (0.7–3) $\times 10^{37}$ (White et al. 1983; Nagase et al. 1991) and 2×10^{37} (Makishima et al. 1990b) ergs s^{-1}, respectively, when the CRSFs were observed. Persistent luminosities of Her X-1 and 4U 1538−52 are $\sim 3 \times 10^{37}$ and $\sim 2 \times 10^{36}$ ergs s^{-1}, respectively. On the other hand, *Ginga* observations have so far failed to reveal CRSFs in very luminous ($> 5 \times 10^{37}$ ergs s^{-1}) pulsars, including Cen X-3, SMC X-1, and LMC X-4, although their spectra can be well fitted with the same equation (1) with rather large values of W. We suggest that X-ray luminosities above $\sim 4 \times 10^{37}$ ergs s^{-1} tend to wash out CRSFs through the same mechanism as mentioned above. It is intriguing to note that the suggested critical luminosity for the presence of a sharp CRSF, $\sim 4 \times 10^{37}$ ergs s^{-1}, is comparable to the transition luminosity between fan-beam and pencil-beam emission patterns (Parmar, White, & Stellar 1989).

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