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DISCOVERY OF A PROMINENT CYCLOTRON ABSORPTION FEATURE FROM THE TRANSIENT X-RAY PULSAR X0331+53

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ABSTRACT

A remarkable absorption feature at 28.5 keV, attributable to electron cyclotron resonance, has been discovered in the 1.9–60 keV X-ray spectrum of the recurrent transient X-ray pulsar X0331+53 (V0332+53). The observed resonance energy implies a neutron star surface magnetic field of $2.5(1+z) \times 10^{12}$ G, where z is the gravitational redshift. The detection was made with the *Ginga* observatory in 1989 October, during an outburst of this transient with a flux level of ~0.3 Crab. The feature is very deep and has been resolved with excellent statistics. This is the fourth unambiguous detection of cyclotron resonant scattering features from X-ray pulsars, suggesting that these features are a common phenomenon among these objects. An empirical relation found between the cyclotron resonance energy and the spectral cutoff energy suggests that the magnetic field strengths of the known X-ray pulsars are clustered in a range $(1\text{–}4) \times 10^{12}$ G.

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

I. INTRODUCTION

Observations of cyclotron resonance features in the radiation spectra from magnetized objects provide a powerful way to determine their magnetic field strength B. For magnetized neutron stars which are believed to have $B \sim 10^{12}$ G, X-ray observations are important (Mészáros and Nagel 1985; Wang, Wasserman, and Salpeter 1989) because their electron cyclotron resonance energy, $E_a = 11.6 \times (B/10^{12}\ \mathrm{G})$ keV, is expected to fall in the hard X-ray range.

In this research field, a series of new results have been obtained with the *Ginga* X-ray observatory. Following the discovery of harmonic cyclotron absorption lines in γ-ray bursts by Murakami *et al.* (1988), a cyclotron resonant scattering feature (CRSF) was discovered at an X-ray energy $E_a \sim 20$ keV from the X-ray pulsar 4U 1538−52 (Clark *et al.* 1990). Observations of Her X-1 by Mihara *et al.* (1990) show that the long-known 30–60 keV cyclotron feature of this "prototype cyclotron object" (Trümper *et al.* 1978; Voges *et al.* 1982; Soong *et al.* 1990) appears in absorption at $E_a \sim 34$ keV rather than in emission at ~55 keV. Nagase *et al.* (1990) confirmed the harmonic CRSFs at 12 and 24 keV in the recurrent transient pulsar 4U 0115+63 (Wheaton *et al.* 1979; White, Swank, and Holt 1983). Here we report on another novel *Ginga* result, i.e., discovery of a 28.5 keV CRSF from the recurrent transient X0331+53.

II. OBSERVATIONS

The recurrent transient pulsar X0331+53 (V0332+53; Stellar *et al.* 1985; Whitlock 1989; Makishima *et al.* 1990, hereafter Paper I) forms a 34 day binary together with a Be companion, BQ Cam (Argyle *et al.* 1983; Kodaira *et al.* 1985; Corbet, Charles, and van der Klis 1986). Its X-ray outbursts had been recorded twice, in 1973 (Whitlock 1989) and in 1983–1984 (Stella *et al.* 1985; Paper I), until the *Ginga* All Sky Monitor (ASM; Tsunemi *et al.* 1989) detected its sudden emergence on 1989 September 19 (Makino *et al.* 1989*a*). We monitored the outburst evolution with the ASM to find that the source reached a peak intensity of ~0.4 Crab in the middle of October and stayed there at least until the end of the month. During this period of activity, we occasionally pointed the Large Area Proportional Counters (LAC; Turner *et al.* 1989) to X0331+53 for detailed spectral and timing studies. As observed in the 1983 outburst, the source exhibited a very hard spectrum, violent flickering, and shallow, 4.37 s, pulsations. Details of the outburst light curve and timing results will be reported elsewhere.

We acquired 1.7–36 keV LAC spectra of X0331+53 on several occasions during September 20–30, in which a diplike feature was noticed at ~30 keV (Makino *et al.* 1989*b*). In order to confirm this finding, we expanded the LAC energy range to 1.9–60 keV by reducing the high voltage to 1760 V (normally 1830 V). Figure 1*a* shows the wide-band pulse-height spectrum of X0331+53 thus acquired on October 1, 18:57–22:20 UT, when the source intensity was ~0.3 Crab. We subtracted background data obtained from a nearby sky region. Due to limited time resolution (16 s), the spectrum is averaged over the 4.37 s pulse period. The spectrum indeed exhibits an outstanding feature at 30–40 keV, which is better visualized in Figure 1*c* where we have normalized the spectrum to that of the Crab Nebula (a power law with photon index ~2.1; Turner *et al.* 1989) obtained in the same way.

The feature appears near the K-edge, at 35 keV, of xenon contained in the detector gas (20% Xe, 75% Ar, 5% CO_2). However, the amplitude of the observed feature (~0.5 counts $\mathrm{s^{-1}\ keV^{-1}}$) is much larger than the Xe K-edge structure in the background spectrum (an excess hump of ~0.1 counts $\mathrm{s^{-1}\ keV^{-1}}$ at ~35 keV), and far exceeds the general background uncertainty (~0.01 counts $\mathrm{s^{-1}\ keV^{-1}}$ at ~30 keV; Hayashida *et al.* 1989). We note that, after proper background subtraction, the source spectrum still exhibits an instrumental K-edge structure, including an apparent hump just above ~35 keV

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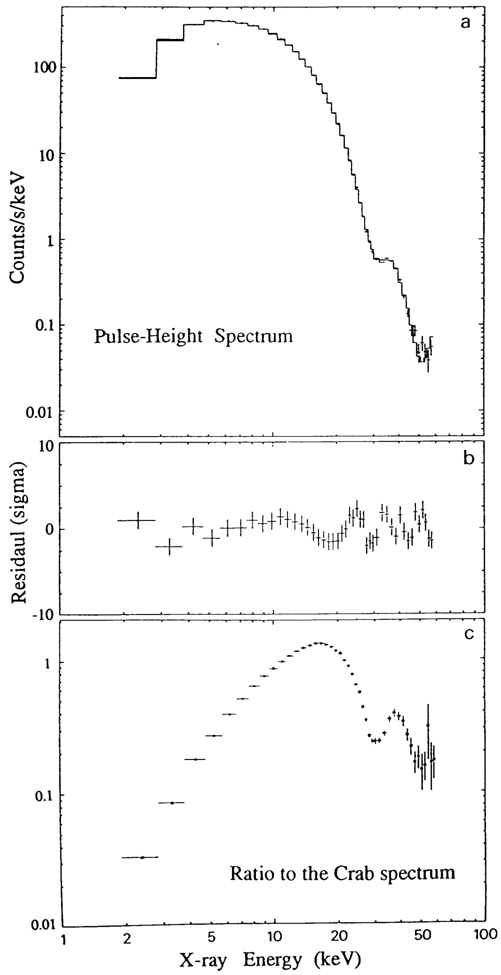

FIG. 1.—(*a*) The 1.9–60 keV X-ray pulse-height spectrum of X0331+53 observed with the *Ginga* LAC, displayed without removing the detector response. The best-fit cyclotron absorption model convolved through the detector response is shown as a histogram. (*b*) Fit residuals in units of standard deviation. (*c*) Ratios of the spectrum of (*a*), to the pulse-height spectrum of the Crab Nebula obtained on 1987 March 14.

due to the increased detector efficiency. The relative amplitude of this instrumental hump has been determined to be $\sim$25% through prelaunch calibration, Monte Carlo simulation, and in-orbit Crab calibration. This is insufficient by more than a factor of 3 to explain the spectral feature observed from X0331+53. Furthermore, any instrumental artifacts should be canceled out in the ratio of the source spectrum to the Crab spectrum (Fig. 1*c*).

We can thus conclude with great confidence that the observed 30–40 keV feature is not instrumental, but intrinsic to X0331+53. We interpret it as a cyclotron structure, because its energy is far away from that of any atomic line or edge due to abundant elements. The feature can be modeled either by a $\sim$30 keV absorption dip or a $\sim$38 keV emission peak. However, the latter would require too complex a shape for the underlying continuum, bending steeply above $\sim$17 keV and then flattening above $\sim$40 keV relative to the Crab spectrum (Fig. 1*c*); assuming such an artificial continuum shape would not be warranted. Moreover the cyclotron features so far observed, from 4U 1538−52 (Clark *et al.* 1990), Her X-1 (Mihara *et al.* 1990), and 4U 0115+63 (Nagase *et al.* 1990), all appear in absorption rather than emission. Therefore, we further conclude that X0331+53 exhibits an absorption feature at $\sim$30 keV.

III. DATA ANALYSIS AND RESULTS

To fit the observed spectrum we employ a model photon-number distribution of the form

$$f(E) = IE^{-\alpha} \exp\left[-H(E) - N_{\rm H}\sigma(E)\right] . \tag{1}$$

We convolve it through the detector response, which includes proper knowledge of the Xe K-edge effects, to compare it with the data. Here E is the X-ray photon energy, I is the normalization, α is the photon index, $N_{\rm H}$ is the neutral column density, σ is the photoelectric absorption cross section, and

$$\begin{aligned} H(E) = {} & A_1(W_1 E/E_{a1})^2/[(E - E_{a1})^2 + W_1^2] \\ & + A_2(W_2 E/E_{a2})^2/[(E - E_{a2})^2 + W_2^2] \end{aligned} \tag{2}$$

is a six-parameter empirical model for the CRSF derived from the classical cross section for resonant cyclotron scattering in magnetized plasmas (Tanaka 1986). The suffixes 1 and 2 refer to the fundamental and 2nd harmonic resonances respectively, while E_a, A, and W represent the position, depth, and width of the CRSF respectively. The second harmonic energy E_{a2} is left free to vary rather than be fixed at a value near $2E_{a1}$. Although the formula may be too simplified to represent the physics actually taking place in the pulsars, it can be used as a convenient phenomenological fitting model to describe the CRSF simultaneously with the high-energy cutoff (HEC) that is characteristic of X-ray pulsar spectra. For those pulsar spectra without noticeable CRSFs, the model has in fact reproduced the HEC successfully, yielding a prediction of $E_a = 28(+15, -4)$ keV for X0331+53 based on the *Tenma* spectrum (Paper I). For the *Ginga* spectra of 4U 1538−52 (Clark *et al.* 1990) and Her X-1 (Mihara *et al.* 1990), the CRSF and the HEC have been described by this model in a consistent way.

The results of this fitting are shown in Figure 1*a*, with the fit residuals in Figure 1*b* and the best-fit parameters in Table 1. The results undoubtedly establish the existence of a deep ($A_1 = 2.9 \pm 0.2$) absorption trough at $E_{a1} = 28.5 \pm 0.5$ keV, and confirm the conjecture of $E_a = 28(+15, -4)$ keV made in Paper I. Identifying E_{a1} with the cyclotron resonance energy, we estimate the surface magnetic field to be $B = 2.5(1 + z) \times 10^{12}$ G, where z is the gravitational redshift. The spectrum exhibits no hint of iron K-line above a 90% confidence upper limit of 40 eV in equivalent width, in agree-

TABLE 1

RESULTS OF THE MODEL FITTING TO THE OBSERVED SPECTRUM[a]

Parameter	Value
Normalization I (photons s^{-1} cm^{-2} keV^{-1})	0.24 ± 0.02
Photon index α	0.47 ± 0.05
Depth of resonance A	2.9 ± 0.2[b]; 3.1 ± 0.4[c]
Cyclotron resonance energy E_a (keV)	28.5 ± 0.5[b]; 52.6 ± 1.4[c]
Width of resonance W (keV)	11.0 ± 0.9[b]; 10 ± 3[c]
Absorbing column $N_{\rm H}$ (cm^{-2})	$(4 \pm 1) \times 10^{22}$
Degrees of freedom	36
Reduced χ^2	1.91
2–20 keV energy flux (ergs s^{-1} cm^{-2})	$(1.9 \pm 0.2) \times 10^{-8}$
2–20 keV luminosity at 3 kpc[d] (ergs s^{-1})	$(2.0 \pm 0.2) \times 10^{37}$

[a] The quoted errors refer to single-parameter 90% confidence limits.
[b] For the fundamental resonance.
[c] For the second harmonic resonance.
[d] See Corbet, Charles, and van ker Klis 1985 for distance estimates.

ment with Paper I. The reduced χ^2 of the fit, 1.91 for 36 degrees of freedom, suggests that the model is yet to be improved, although this is beyond the scope of this *Letter*.

The second harmonic resonance has so far been established in the spectra of gamma-ray bursts (Murakami *et al.* 1988) and 4U 0115+63 (Nagase *et al.* 1990). For X0331+53, the second harmonic term has formally turned out to be quite significant ($A_2 = 3.1 \pm 0.4$), and the observed ratio $E_{a2}/E_{a1} = 1.85 \pm 0.07$ is close to the value, 1.93, calculated assuming $z = 0.3$ and taking into account special relativistic effects. However, since we have little spectral information in the energy range above the inferred second harmonic energy ($E_{a2} = 53$ keV), these results on the second harmonic in X0331+53 should be taken only as hint rather than a firm evidence. The second term in equation (2) may simply simulate a gradual turnover in the underlying continuum, to compensate the oversimplified continuum shape (i.e., a single power law) employed in equation (1).

Figure 2 gives the inferred incident spectrum of X0331+53, after removing the instrumental response using the best-fit model. This result in fact depends little on the fit model used for the deconvolution, because the observed feature, with a width of $W_1 = 11$ keV, has been well resolved by the LAC which has a FWHM energy resolution of $\sim 8\%$ at 30 keV. The resonance feature is now free from the Xe K-edge effects.

IV. DISCUSSION

The present discovery makes the fourth unambiguous detection of CRSF from X-ray pulsars; the detections now include an X-ray pulsar with a late-type companion (Her X-1), that with an OB supergiant (4U 1538−52), and recurrent transients with Be companions (4U 0115+63 and X0331+53). We therefore suggest that the CRSF should be observed from accretion-powered X-ray pulsars as a rule rather than an exception, regardless of their environment. However, X0331+53 is of particular importance among the four, since it exhibits by far the most prominent CRSF which has been resolved with a superior signal-to-noise ratio. We believe that the present results provide valuable data to which theoretically calculated X-ray pulsar spectra should conform.

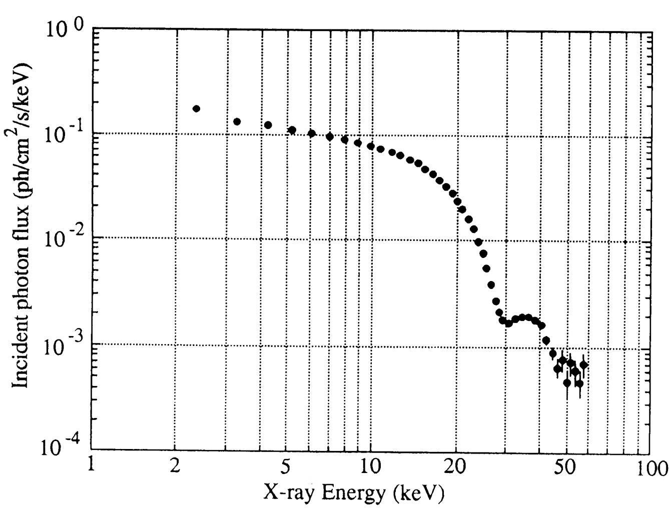

FIG. 2.—The inferred incident photon spectrum of X0331+53, displayed with the low-energy photoelectric absorption reset to zero for simplicity. The instrumental response has been removed using the best-fit model shown in Fig. 1*a* and Table 1.

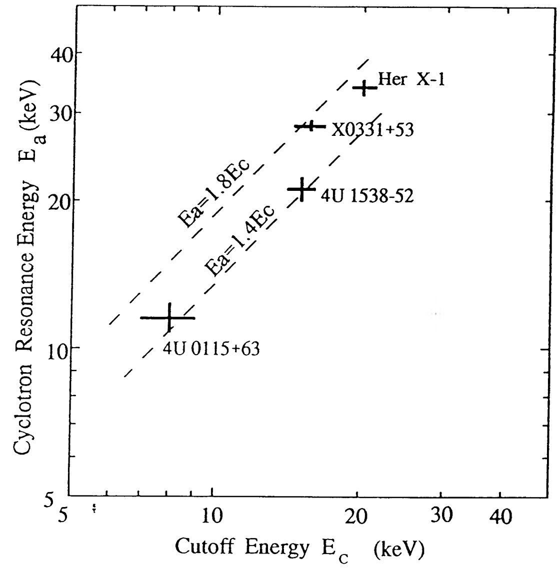

FIG. 3.—Relation between the cutoff energy E_C and the cyclotron energy E_a for the four X-ray pulsars with established cyclotron features. We adopt $E_a = 12$ keV for 4U 0115+63 (Nagase *et al.* 1990). Values of E_C for Her X-1 and 4U 0115+63 are taken from White, Swank, and Holt (1983), while those for 4U 1538−52 and X0331+53 refer to Makishima *et al.* (1987) and Paper I, respectively.

Using a single analytic model, we have successfully described the 1.9–60 keV spectrum of X0331+53, in the sense that the HEC has been expressed in terms of the CRSF parameters (E_a, A, and W) without any additional ad hoc model parameters. This is very similar to the case of 4U 1538−52 (Clark *et al.* 1990) and Her X-1 (Mihara *et al.* 1990). These results support the suggeston that cyclotron resonance is responsible for the formation of the HEC in X-ray pulsar spectra (Pravdo *et al.* 1978; Tanaka 1986). This view is further supported by the simple fact that the CRSF has so far been discovered in those pulsars with the sharpest HECs (White, Swank, and Holt 1983), including X0331+53 itself (Paper I). Therefore, future search for the CRSF should be conducted on pulsars with the next sharpest HECs.

As presented in Figure 3, we find good proportionality between the values of E_a and E_C for the four "cyclotron" pulsars, where E_C measures the energy at which the HEC starts in terms of the exponential cut-off model (White, Swank, and Holt 1983). This result not only strengthens the relation between the two quantities but also enables us to estimate the surface field strengths of X-ray pulsars simply based on the knowledge of their HECs. As the published values of E_C of the known pulsars are clustered between 8 and 20 keV (White, Swank, and Holt 1983), most of them are inferred to have cyclotron energies in the range 12–40 keV; hence $B = (1–4) \times 10^{12}$ G, in gross agreement with the distribution in initial field strength estimated for radio pulsars (Stollman 1987). This narrow scatter in B suggests that the magnetic field of X-ray pulars do *not* decay within the typical lifetimes of massive X-ray binaries ($\sim 10^7$ yr). The possibly much greater age of Her X-1 (with a late-type primary) may demand a still longer field decay time. These implications potentially have a very large impact on the distribution and evolution of magnetic fields in neutron stars.

We must, however, notice that selection effects may prevent detection of X-ray pulsars with weaker fields, e.g.,

$B < 7 \times 10^{11}$ G (hence E_C below a few keV). Such objects may be rather hard to detect, or to recognize as X-ray pulsars, because above 2–3 keV their spectra would be steeply cut off. Two extraordinary pulsars X2259+586 (Koyama *et al.* 1989; Hanson *et al.* 1988) and 1E 1048.1−5937 (Corbet and Day 1990), with steep spectra and suggested weak fields (a few times 10^{11} G; Koyama *et al.* 1989), may be such examples. The low age ($<2 \times 10^4$ yr) of X2259+586, estimated on the basis of its association with the supernova remnant G109.1−1.0 (Gregory and Fahlman 1980), further suggests that it was born with a weak field.

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REFERENCES

Argyle, R. W., *et al.* 1983, *IAU Circ.*, No. 3897.
Clark, G., Woo, J., Nagase, F., Makishima, K., and Sakao, T. 1990, *Ap. J.*, **353**, 274.
Corbet, R. H., Charles, P., and van der Klis, M. 1986, *Astr. Ap.*, **162**, 117.
Corbet, R. D. H., and Day, C. S. 1990, *M.N.R.A.S.*, **243**, 553.
Gregory, P. C., and Fahlman, G. G. 1980, *Nature*, **287**, 805.
Hanson, C. G., Dennerl, K., Coe, M. J., and Davies, S. R. 1988, *Astr. Ap.*, **195**, 114.
Hayashida, K., *et al.* 1989, *Pub. Astr. Soc. Japan*, **41**, 373.
Kodaira, K., *et al.* 1985, *Pub. Astr. Soc. Japan*, **37**, 97.
Koyama, K., *et al.* 1989, *Pub. Astr. Soc. Japan*, **41**, 461.
Makino, F., and the *Ginga* Team. 1989*a*, *IAU Circ.*, No. 4872.
Makino, F., and the *Ginga* Team. 1989*b*, *IAU Circ.*, No. 4858.
Makishima, K., Koyama, K., Nagase, F., and Hayakawa, S. 1987, *Ap. J.*, **314**, 619.
Makishima, K., *et al.* 1990, *Pub. Astr. Soc. Japan*, **42**, 295 (Paper I).
Mészáros, P., and Nagel, W. 1985, *Ap. J.*, **298**, 147.
Mihara, T., *et al.* 1990, *Nature*, **346**, 250.
Murakami, T., *et al.* 1988, *Nature*, **335**, 234.
Nagase, F., *et al.* 1990, in preparation.
Pravdo, S. H., *et al.* 1978, *Ap. J.*, **225**, 988.
Soong, Y., Gruber, D., Peterson, L., and Rothschild, R. 1990, *Ap. J.*, **348**, 641.
Stella, L., White, N. E., Davelaar, J., Parmar, A. N., Blissett, R. J., and van der Klis, M. 1985, *Ap. J.* (*Letters*), **288**, L45.
Stollman, G. M. 1987, *Astr. Ap.*, **178**, 143.
Tanaka, Y. 1986, in *Radiation Hydrodynamics in Stars and Compact Objects*, ed. D. Mihalas and K.-H. A. Winkler (Berlin: Springer), p. 198.
Trümper, J., Pietsch, W., Reppin, C., Voges, W., Staubert, R., and Kendziorra, E. 1978, *Ap. J.* (*Letters*), **219**, L105.
Tsunemi, H., Kitamoto, S., Manabe, M., Miyamoto, S., Yamashita, K., and Nakagawa, M. 1989, *Pub. Astr. Soc. Japan*, **41**, 391.
Turner, M. J. L., *et al.* 1989, *Pub. Astr. Soc. Japan*, **41**, 345.
Voges, W., Pietsch, W., Reppin, C., Trümper, J., Kendziorra, E., and Staubert, R. 1982, *Ap. J.*, **263**, 803.
Wang, J., Wasserman, I., and Salpeter, E. 1989, *Ap. J.*, **338**, 343.
Wheaton, Wm., *et al.* 1979, *Nature*, **282**, 240.
White, N. E., Swank, J. H., and Holt, S. S. 1983, *Ap. J.*, **270**, 711.
Whitlock, L. 1989, *Ap. J.*, **344**, 371.

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