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DISCOVERY OF A CYCLOTRON ABSORPTION LINE IN THE SPECTRUM OF THE BINARY X-RAY PULSAR 4U 1538−52 OBSERVED BY *GINGA*

GEORGE W. CLARK AND JONATHAN W. WOO
Department of Physics and Center for Space Research, Massachusetts Institute of Technology
FUMIAKI NAGASE
The Institute of Space and Astronautical Science
AND
KAZUO MAKISHIMA AND TARO SAKAO
Department of Physics, University of Tokyo
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ABSTRACT

A cyclotron absorption line near 20 keV has been found in the spectrum of the massive eclipsing binary X-ray pulsar 4U 1538−52 in observations with the *Ginga* observatory. The line is detected throughout the 529 s pulse cycle with a variable equivalent width that has its maximum value during the smaller peak of the two-peak pulse profile. We find that the profile of the pulse and the phase-dependence of the cyclotron line can be explained qualitatively by a pulsar model based on recent theoretical results on the properties of pencil beams emitted by accretion-heated slabs of magnetized plasma at the magnetic poles of a neutron star. The indicated field at the surface of the neutron star is $1.7(1 + z) \times 10^{12}$ *G*, where *z* is the gravitational redshift.

Subject headings: line identifications — pulsars — stars: individual (4U 1538−52) — stars: magnetic — X-rays: binaries — X-rays: spectra

I. INTRODUCTION

The possibility that electron-cyclotron emission lines might appear in the spectra of X-ray binaries was suggested by Basko and Sunyaev (1975) in a general discussion of the formation of beaming patterns in accreting, magnetized and rotating neutron stars. Features interpreted as cyclotron emission or absorption lines were subsequently discovered in the spectra of the binary X-ray pulsars Her X-1 (Trümper *et al.* 1978; Voges *et al.* 1982) and 4U 0115+63 (Wheaton *et al.* 1979; Rose *et al.* 1979), and evidence of cyclotron resonance effects was found in 4U 1626−67 (Pravdo *et al.* 1979) and X2259+586 (Koyama *et al.* 1989). Mazets *et al.* (1981) reported absorption-like features in numerous gamma-ray burst spectra in the energy range from 30–70 keV. Distinct first and second harmonic absorption features have been observed in the spectra of two gamma-ray bursts by *Ginga* (Murakami *et al.* 1988; Fenimore *et al.* 1988). Extensive theoretical work has been done to clarify the physics of X-ray propagation in magnetized plasmas (see the reviews of Holt and McCray 1982 and references therein; Hayakawa 1985; Basko and Sunyaev 1975, 1976; Ventura 1979; Herold 1979; Kanno 1980; Kaminker *et al.* 1982) and to explain the pulse-phase dependence of spectra which contain cyclotron features (Pravdo *et al.* 1978; Kanno 1980; Nagel 1981; Pravdo and Bussard 1981; Mészáros and Nagel 1985; Kii *et al.* 1986).

We describe here a cyclotron absorption line discovered in the spectra of the massive eclipsing binary X-ray pulsar 4U 1538−52 obtained with the *Ginga* X-ray observatory. The source was first detected by *Uhuru* (Giacconi *et al.* 1974). Pulsations with a period of 529 s were subsequently found in data from *Ariel 5* (Davison, Watson, and Pye 1977), and from *OSO* 8 (Becker *et al.* 1977). The latter also revealed eclipses and Doppler modulation of the pulse period implying an orbital period of 3.73 days. Improved position measurements with *SAS 3* (Apparao *et al.* 1978) led to identification of the optical counterpart as a B0 supergiant (Cowley *et al.* 1977; Crampton, Hutchings, and Cowley 1978; Ilovaisky, Chevalier, and Motch 1979) and an estimated distance of 5.5 kpc. *HEAO 1* observations yielded pulse profiles in three broad spectral ranges from 1 to 25 keV (White, Swank, and Holt 1983). Analysis of *Tenma* data (Makishima *et al.* 1987) provided a refined orbital ephemeris, a measure of the spin-down rate of the pulsar, a multichannel spectral analysis that showed the presence of a weak iron emission line, and measures of the extended atmosphere of the primary star in the gradual eclipse transitions. Our observations contain similar information with improved statistical accuracy which will be presented in subsequent publications. Here we describe the cyclotron feature and the energy dependence of the pulse profiles, and show that the observations can be modeled as X-ray emission from slabs of magnetized plasma at the bases of the accretion flow onto the neutron star.

II. OBSERVATIONS AND DATA ANALYSIS

Our observations were made with the Large Area Counter (LAC) of the *Ginga* satellite observatory during 1988 February 29 to March 3, covering a complete 3.7 day orbital cycle of the pulsar. The LAC is a proportional gas counter with a total effective area of 4000 cm^2, a field of view of $1^\circ.1 \times 2^\circ.0$ FWHM, an energy range from 1 to 36 keV, and an energy resolution of 20% FWHM at 5.9 keV. Counts were recorded in 48 pulse-height channels with various binning times from 0.5 to 16 s. The satellite and its instrumentation have been described by Makino (1987), and details of the LAC instrument by Turner *et al.* (1989).

The pulse height spectrum, averaged over the orbital cycle exclusive of the 100° interval of orbital phase affected by the eclipse, shows a conspicuous negative deviation around 20 keV from the least-squares fit of a calculated spectrum derived by convolving the LAC response function with an incident energy spectrum of the form introduced by Pravdo *et al.* (1978) and widely used to fit the spectra of massive binary X-ray sources, namely a power law with a high-energy exponential cutoff and photoelectric absorption. The negative deviation can be fitted well if the fitting function is multiplied by a factor representing an absorption line at 20 kV. The average energy flux of the fitted incident spectrum without the photoelectric absorption factor is then found to be 1.2×10^{-9} ergs cm^{-2} s^{-1} from 0.5 to 60 keV, which agrees well with the results from the *HEAO 1* observations (White, Swank, and Holt 1983) and implies a luminosity of $10^{36.6}$ ergs s^{-1} at a distance of 5.5 kpc (Crampton, Hutchings, and Cowley 1978) if the observed phase-averaged spectrum without absorption is assumed to be the same as the total emission spectrum at the source. This luminosity is close to the critical value defined by Basko and Sunyaev (1976) below which the free fall zone of the accretion flow is expected to extend to near the surface of the neutron star.

We prepared spectrally resolved pulse profiles in ten energy ranges from 1.1 to 38.2 keV, binning the data according to the pulse phase and taking account of the Doppler variations caused by orbital motion in the binary system. The background-subtracted profiles are displayed in Figure 1 with the zero of phase set to coincide with the center of the larger peak of the two-peak pulse cycle. The profiles have the general form of a primary and secondary pulse with centers separated by 180°. Substantial variations in the pulse profiles from one energy interval to another are evident. In particular, the 20 keV feature is strikingly apparent in the virtual disappearance of the secondary peak in the 20.9–25.7 keV energy range. Also noteworthy are a dimple in the center of the primary pulse in the lowest energy bin, and an increase of the pulsed fraction with energy. Both of these latter characteristics are evident in the earlier *HEAO 1* data (White, Swank, and Holt 1983).

Figure 2 displays the portion of the same data as pulse-height spectra in eight equal pulse-phase bins defined in Table 1. For our present purposes we confine our spectral analysis to

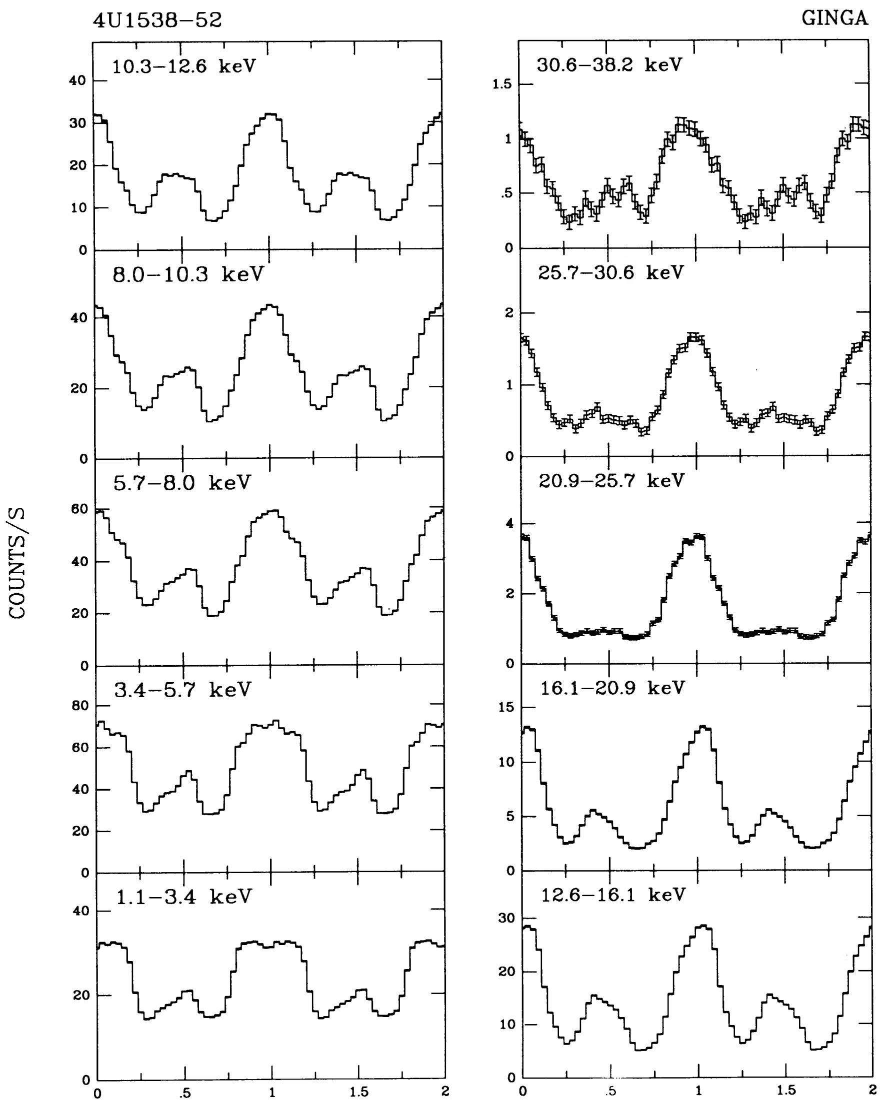

FIG. 1.—Average pulse profiles (background subtracted) of 4U 1538−52 in ten pulse height intervals. Zero phase has been set to coincide with the middle of the larger peak. The virtual disappearance of the smaller peak in the interval of pulse heights corresponding to the energy interval from 20.9 to 25.7 keV reflects the presence in the spectrum of an absorption line whose equivalent width has a maximum near phase 0.5 of the pulse cycle.

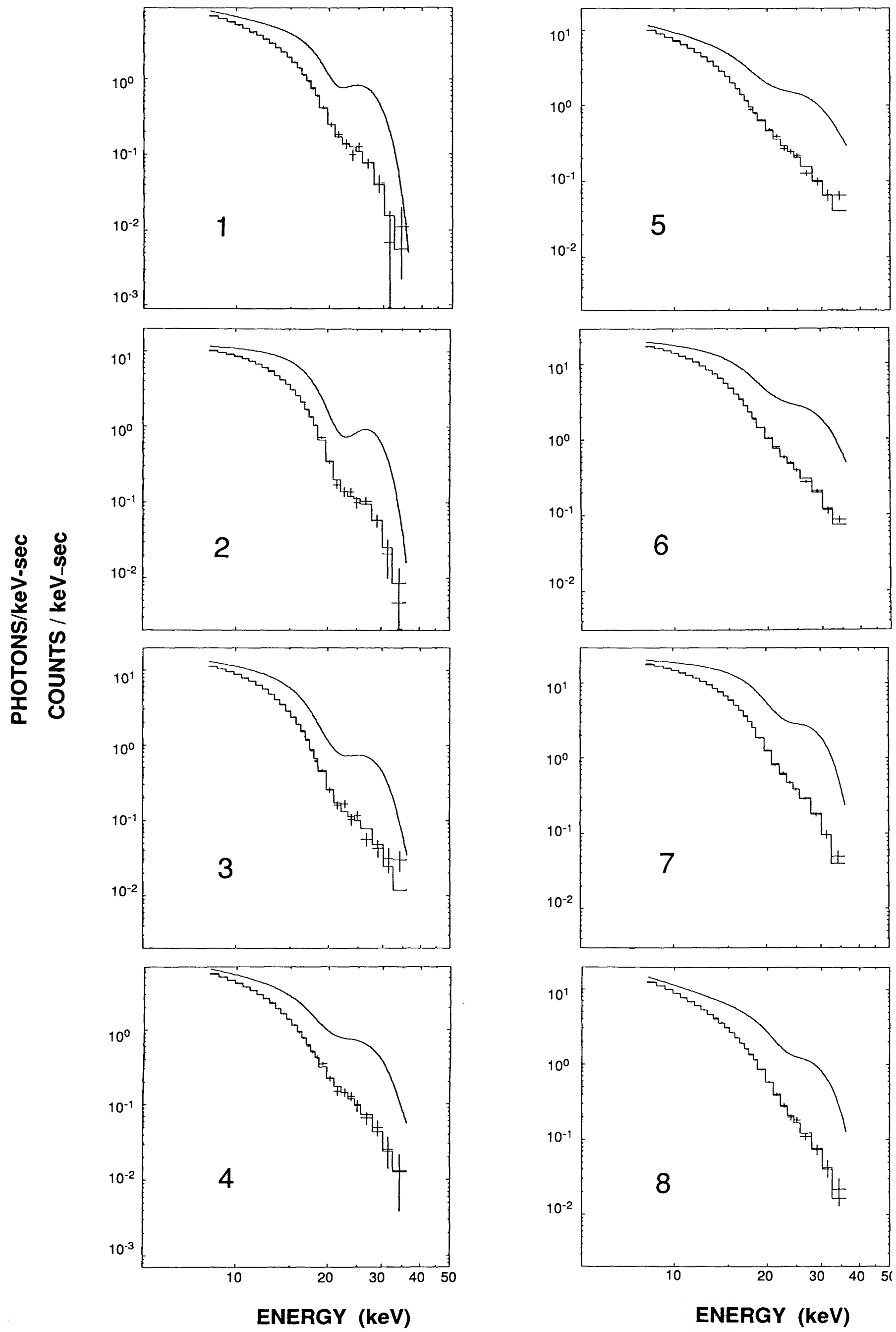

FIG. 2.—Pulse-height spectra (counts keV^{-1} s^{-1}) of 4U 1538−52 in eight equal phase intervals of the pulse cycle. Above each histogram of counting rates is the fitted incident energy spectrum (photons keV^{-1} s^{-1}) before convolution with the LAC response function.

TABLE 1

PARAMETERS OF THE TRIAL FUNCTION (EQ. 1) FITTED TO THE PULSE HEIGHT SPECTRA

PHASE CENTER		$I \times 10^{\alpha}$							
bin	phase	ph s^{-1} keV^{-1}	α	A_1	E_a (keV)	W (keV)	ew (keV)	A_2	χ^2/DOF
1..........	0.31	7.2 ± 0.3	0.74 ± 0.11	1.22 ± 0.20	20.7 ± 0.5	3.6 ± 0.9	8.6 ± 1.1	12.6 ± 8.1	0.80
2..........	0.44	12.1 ± 0.6	0.07 ± 0.10	2.07 ± 0.21	21.4 ± 0.3	4.3 ± 0.6	13.3 ± 0.7	13.9 ± 5.5	1.40
3..........	0.56	12.8 ± 0.6	0.41 ± 0.15	1.87 ± 0.29	20.3 ± 0.6	5.4 ± 1.2	13.3 ± 0.8	7.3 ± 3.8	1.36
4..........	0.69	5.9 ± 0.3	0.72 ± 0.21	1.01 ± 0.21	19.4 ± 0.7	5.3 ± 1.8	9.0 ± 1.3	4.2 ± 2.5	0.93
5..........	0.81	10.1 ± 0.5	0.84 ± 0.18	0.81 ± 0.12	19.1 ± 0.6	6.0 ± 1.6	8.2 ± 0.8	2.5 ± 0.8	2.39
6..........	0.94	20.2 ± 1.0	0.24 ± 0.11	1.07 ± 0.08	20.1 ± 0.4	6.7 ± 0.8	10.7 ± 0.4	4.0 ± 0.8	1.73
7..........	0.06	20.7 ± 1.0	0.17 ± 0.08	1.16 ± 0.09	21.6 ± 0.3	5.4 ± 0.6	10.8 ± 0.5	8.1 ± 1.8	1.47
8..........	0.19	11.7 ± 0.6	1.15 ± 0.08	0.77 ± 0.17	22.2 ± 0.9	4.7 ± 1.6	7.5 ± 1.3	7.9 ± 5.9	1.07

the energy range above 8 keV to avoid the complications of low-energy absorption and iron Kα emission. The superposed histograms are fitted pulse-height spectra derived from assumed incident energy spectra represented by the formula

$$\frac{dN}{dE} = IE^{-\alpha} \exp\left[-\frac{A_1 W^2(E/E_a)^2}{(E-E_a)^2+W^2} - \frac{A_2(2W)^2(E/2E_a)^2}{(E-2E_a)^2+(2W)^2}\right], \quad (1)$$

where E is the X-ray energy expressed in units of 1 keV. The formula represents a power law continuum with absorption features in the form of a Lorentzian × E^2, resembling the first and second harmonic resonance absorption curves derived by Herold (1979) in a treatment of Compton scattering in strongly magnetized accretion flows. A subsequent relativistic quantum mechanical calculation by Herold, Rudder, and Wunner (1981) yielded cross sections with resonance features of a substantially different form. However, equation (1) serves our purpose in being computationally convenient and having just enough parameters to adjust the gross features of incident spectra to fit the observed pulse-height spectra, namely the total intensity above 8 keV, determined mainly by I and α, an absorption feature with center energy E_a, depth A_1, and width W, and a high-energy cutoff determined by A_2. The fitted functions, representing the incident energy spectra before convolution with the detector efficiency function, are also displayed in Figure 2. The fitted values of the six parameters are listed in Table 1 together with errors and the reduced χ^2 values of the fits. In each case, the quoted errors define single-parameter 90% confidence limits were the other five parameters have been refitted to minimize χ^2. Also tabulated are measures of the equivalent width, *ew*, of the absorption feature defined by the formula

$$ew = E_a \int_{e_1}^{e_2} \left\{\exp(-A_1 w^2) - \exp\left[-\frac{A_1 w^2 e^2}{(e-1)^2+w^2}\right]\right\} de, \quad (2)$$

which is designed to circumvent the problem of the nonzero asymptotic value of the absorption factor. In this formula $e = E/E_a$, $w = W/E_a$, $e_1 = (1 + w^2)/2$, and $e_2 = 2$. We cut the integral off at 2 because of the absence of data above $2E_a$. The errors tabulated for *ew* are also 90% confidence errors derived in each case from the distribution of the calculated values of *ew* in a thousand trials with values of E_a, A_1, and W chosen at random from Gaussian distributions with standard deviations equal to 0.61 times their 90% confidence errors. As indicated above, the second harmonic absorption "line" centered at $2E_a$ serves essentially as a high energy cutoff in our fitting process. The absence of data above $2E_a$ precludes any definite conclusion regarding its actual presence in the incident spectrum.

We tried fitting several other functions to the phase-resolved spectral data, namely: (1) a power law with exponential cutoff and a single-absorption line near 20 keV in the form of the first of the two exponential factors in equation (1); (2) a power law with exponential cutoff and a Gaussian absorption line near 20 keV; (3) a Planck function with an absorption line near 20 keV in the form of the first of the two exponential factors in equation (1); (4) a power law with exponential cutoff and a Gaussian *emission* line above 20 keV; (5) the sum of two power laws with exponential cutoffs, intended to represent the combined spectrum of emissions from two separate regions; (6) the sum of a power law with exponential cutoff and a Planck function with a positive slope in the region of the feature near 20 keV. Functions (1) and (2) fit the data in all phase bins as well as does equation (1) with essentially identical values for the center energies and depths of the absorption feature. However, an exponential cutoff has no apparent physical interpretation. Moreover, high-quality spectra obtained with *Tenma* and *Ginga* for several X-ray pulsars, including Cen X-3, Her X-1, X0331+53, and GX 301–2, are not fitted well by a power law with exponential cut off, and the fit residuals show systematic deviations (Makishima *et al.* 1989). Function (3) gives satisfactory fits in all phase bins except 4 and 8. Here, again, the fitted absorption line positions and depths are consistent with those obtained with equation (1). Functions (4–6) do not give as good fits as do (1) and (2) for any phase bins, although the Gaussian emission line of (4) can provide a sharp peak on the high side of 20 keV, which is essential to achieving satisfactory fits. No incident spectrum with a monotonically decreasing intensity above 10 keV like (5) can yield an inflection in the predicted pulse height spectrum like that observed near 20 keV in the actual data. Even the E^2 dependence of the Planck component of (6), which can be made to dominate the function in the region from 20 to 30 keV given a sufficiently high and implausible value of kT, fails to provide a sufficient change in curvature at 20 keV.

Only the functions with an absorption line near 20 keV yielded acceptable fits. This, and the fact that the secondary pulse virtually disappears in the 20.9–25.7 keV pulse profile of Figure 1 and reappears at higher energies, supports an interpretation of the 20 keV features as an absorption line that is present in all the phase-resolved spectra of Figure 2 and most prominent during the secondary peak of the pulse cycle.

Figure 3 shows plots of the tabulated values of $I \times 10^{\alpha}$, α, E_a, and *ew* against the pulse phase in two cycles. Statistically significant variations correlated with phase are evident. The equivalent width measure, *ew*, has its maximum value during the secondary pulse and a probable secondary maximum during the primary pulse. The center energy of the absorption feature varies by ~15% and is a maximum near the center of the primary pulse.

III. DISCUSSION

An absorption line at 20 keV caused by an electron-cyclotron resonance in the Compton scattering cross section implies a magnetic field in the source with a strength of $1.7(1 + z) \times 10^{12}$ *G*, where $(1 + z)$ is the gravitational redshift factor $(1 - 2GM/c^2R_0)^{-1/2}$ at the surface of the neutron star.

The existence of a prominent cyclotron resonance absorption feature in the spectrum implies that most of the X-rays originate in a region of fairly uniform field strength. Since the field varies rapidly with position near the surface of the neutron star, one must conclude that the radial thickness and lateral spread of the emission region are small compared to the radius of the neutron star.

We have compared our observations with calculated pulse profiles and spectra of pulsar models based on the theoretical work of Nagel (1981) and of Mészáros and Nagel (1985) on radiative transfer of X-rays in highly magnetized plasmas at the magnetic poles of an accreting neutron star, either in the form of a thin slab at the base of the accretion column, or of cylinders representing the accretion columns themselves. Nagel computed the directional dependence of the photon flux at several energies escaping from magnetized plasmas in slab and column geometries. In an extension of this work, Mészáros and Nagel calculated the combined direction and energy depen-

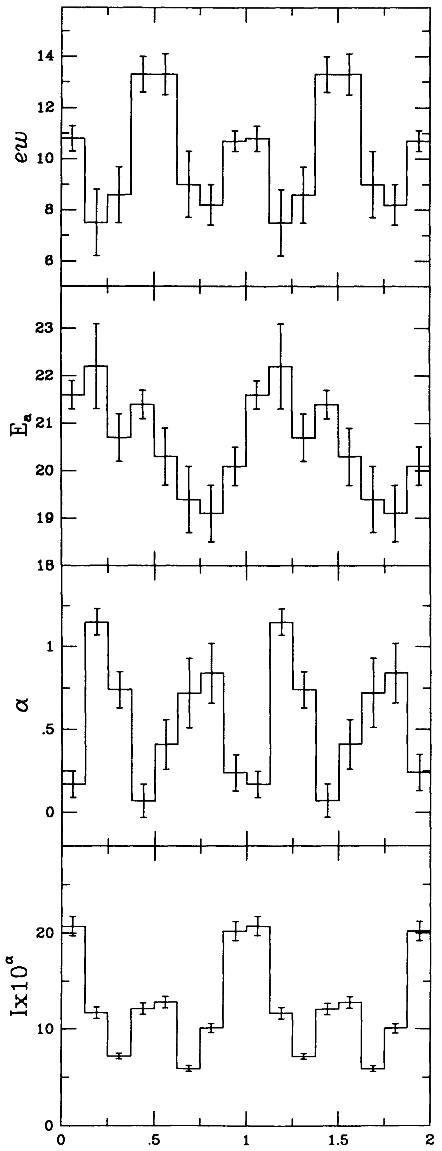

FIG. 3.—Plots of the fitted values of the parameters I, α, E_a and the calculated values of *ew* against phase in the pulse cycle.

dence of the emissions from slab and column geometries, taking into account the effects of cyclotron resonance in the scattering cross section on the spectrum of the emergent radiation and obtaining results on the strength and shape of the resulting cyclotron absorption line. Emission from a column geometry produces a fan beam concentrated near the plane of the dipole equator; emission from a slab produces broad pencil beams concentrated in opposite directions along the magnetic dipole axis. As the neutron star rotates, the X-ray flux at a distant observer pulses with a profile that depends on the emission pattern of the source, the angle between the dipole axis and the rotation axis, and the inclination of the rotation axis.

The particular conditions of the emitting plasmas assumed in the Mészáros and Nagel calculations, intended to approximate those of Her X-1, do not match those of 4U 1538−52. Nevertheless, we have taken their results as a point of departure to construct a pulsar model that mimics the following prominent characteristics of the pulse profiles and spectra of 4U 1538−52:

1. A pulsating component with two broad peaks 180° apart in phase and with an amplitude ratio at 10 keV of 0.44/1.
2. A broadening of the larger peak at lower energies with a dimple in its center in the lowest energy channel (1.1–3.4 keV).
3. An absorption line near 20 keV at all phases but strongest in the phase interval centered on the smaller peak of the pulse profile.

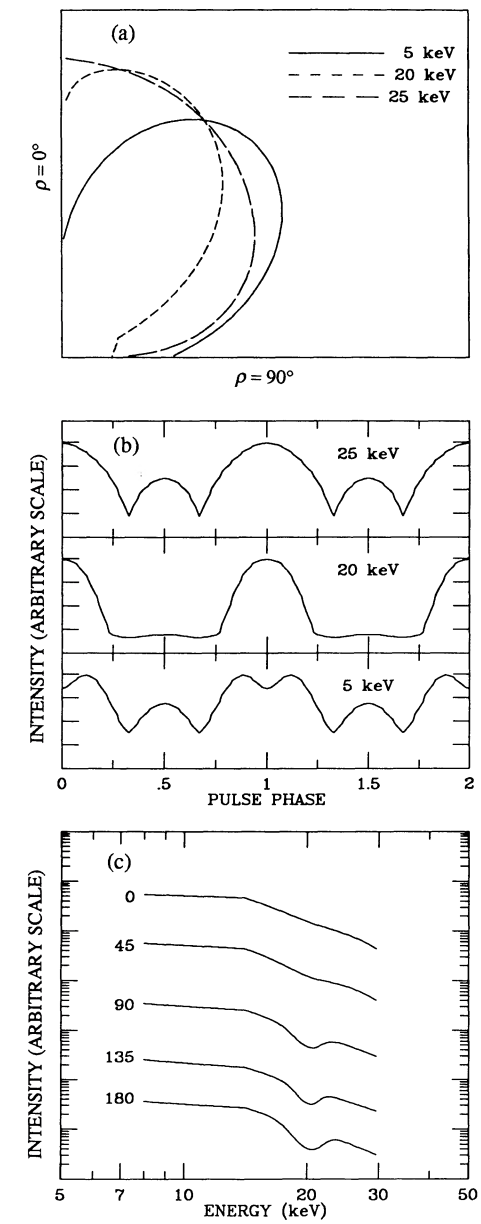

FIG. 4.—(*a*) Polar plot of the assumed radiation intensity from a slab of strongly magnetized plasma with a cyclotron resonance energy of 20 keV. The $\rho = 0°$ line is in the direction of the magnetic dipole axis and perpendicular to the slab. The slope discontinuity in the 20 keV pattern at $\rho = 70°$ is an effect of the cyclotron absorption line which is assumed to have its maximum equivalent width at this angle. (*b*) Pulse profiles computed for a model pulsar radiating from its two poles with the radiation patterns shown above and a configuration in which the dipole axis makes an angle $\Psi = 45°$ with the rotation axis, and the rotation axis makes an angle of $\Theta = 65°$ with the line of sight. (*c*) Average spectra of X-rays received from the model pulsar in five equal phase intervals centered on phases 0°, 45°, 90°, 135°, and 180°.

4. An unmodulated component with a spectrum softer than that of the pulsating component.

We call ρ the angle between the dipole axis and our line of sight, Ψ the angle between the axis of the magnetic dipole and the rotation axis, Θ the inclination of the rotation axis with respect to the line of sight. At the outset we assume that a lower limit can be placed on Θ which is the same as the lower limit of 60° on the orbital inclination deduced from the duration of the eclipse (Rappaport and Joss 1983).

A fan beam with a flux that declines monotonically from the dipole equator to the poles yields a pulse profile with two broad peaks of equal amplitude. The profiles calculated for column geometries by Nagel are predominately of this character. In certain energy ranges they do have shallow minima at $\rho = 90°$ which can give rise to more complex pulse profiles. Nevertheless, column models do not provide a plausible explanation of the characteristics of 4U 1538−52. Furthermore, as noted above, the luminosity of 4U 1538−52 is small enough that the free-fall zone of the accretion flow may extend to the surface of the neutron star giving rise to X-ray emission from a slab geometry (Basko and Sunyaev 1976).

Pencil beams emitted in opposite directions from accretion-heated slabs at the two poles in configurations in which $\Theta + \Psi > 90°$ and $\Theta \neq 90°$ yield pulse profiles with two broad peaks of unequal amplitude 180° apart in phase, like the first of the prominent features of the 4U 1538−52 pulse profiles listed above. For a given radiation pattern the ratio of amplitudes of the primary and secondary pulses depends on the ratio $(\Theta - \Psi)/(180° - \Theta - \Psi)$. The second feature finds a simple explanation in the expected decrease in optical thickness of a strongly magnetized slab in the direction of the field and perpendicular to the slab. This depresses the emission near $\rho = 0°$ and can cause a dimple in the primary peak of the profile at low energies (Basko and Sunyaev 1976; Nagel 1981) as the dipole axis sweeps close to the line of sight where $\rho = \Theta - \Psi$. The calculations of Mészáros and Nagel of slab spectra at emission angles $\rho = 21°$, 48°, 71°, and 86° show the effects of the cyclotron resonance in the scattering cross section as an absorption line which decreases in width with increasing ρ and is deeper at 48° and 71° than at 21° and 86°, giving rise to a pulse-phase dependence of the line strength that may be matched to the third feature.

With these considerations in mind we constructed an expression for the X-ray intensity as a function of energy and angle to fit the results of Nagel (1981) on the angular dependence of the intensity from a slab at several energies. We multiplied this by a function representing a cyclotron absorption line at 20 keV having a maximum equivalent width at $\rho = 70°$. We set $\Theta = 65°$ and $\Psi = 45°$ to get a proper ratio of the amplitudes of the primary and secondary peaks, to bring the magnetic axis close enough to the line of sight in the primary peak to get a dimple of the proper depth at low energies, and to have $\rho = 70°$ at pulse phase = 0.5 and thereby achieve a maximum in the equivalent width of the cyclotron line in the secondary pulse. To mimic the fourth feature we added an isotropic component with a softer spectrum since the projection effect for thin slabs causes negligible flux at $\rho = 90°$, and consequently a nearly 100% modulated double-peak pulse profile.

The radiation patterns of the model at three energies are shown as polar plots in Figure 4(*a*). Figure 4(*b*) shows the predicted pulse profiles at 5, 20, and 25 keV. Figure 4(*c*) shows the average spectrum in each of the five equal phase bins centered on phases from 0° to 180°. The four characteristics of the pulse profiles and energy spectra of 4U 1538−52, cited above, are displayed by this simple model. Its qualitative success indicates that the X-ray phenomena of 4U 1538−52 provide an attractive opportunity for detailed quantitative tests of theoretical models of pulsar emission. In addition to these characteristics, more advanced models will have to account for the systematic variation with pulse phase of the center energy, E_e, noted above and displayed in Figure 3.

In summary, we have discovered a cyclotron absorption line at 20 keV in the spectrum of the binary X-ray pulsar 4U 1538−52 in observations with the *Ginga* satellite. This feature, as well as the energy-dependent pulse profiles, can be mimicked by a model in which X-rays are emitted from thin slabs of magnetized plasma at the magnetic poles of an accreting neutron star with a field intensity in the emitting plasma of $1.7(1 + z) \times 10^{12}$ *G*.

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GEORGE W. CLARK and JONATHAN W. WOO: Department of Physics, Massachusetts Institute of Technology, Cambridge, MA 02139

FUMIAKI NAGASE: The Institute of Space and Astronautical Science, 3-1-1, Yoshinodai, Sagamihara, Kanazawa 229, Japan

KAZUO MAKISHIMA and TARO SAKAO: Department of Physics, University of Tokyo, 7-3-1, Hongo, Bunkyo-ku, Tokyo 113, Japan