The Soft Gamma-Ray Spectrum of A0535+26: Detection of an Absorption Feature at 110 keV by OSSE

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ABSTRACT

We present soft γ-ray observations by the Oriented Scintillation Spectrometer Experiment (OSSE) on the Compton Gamma Ray Observatory (GRO) of the transient X-ray binary pulsar A0535+26. The observations were made 1994 February 8–17, immediately prior to the peak of a giant outburst. The phase-averaged spectrum is complex and cannot be described by a single-component model. We find that structure in the spectrum above 100 keV can best be modeled by an absorption feature near 110 keV, which we interpret as the signature of cyclotron resonant scattering. Because of OSSE's 45-keV threshold, we are unable to make a definitive statement on the presence of a 55-keV absorption line; however we can conclude that if this line does exist, it must have a smaller optical depth than the line at 110 keV. A first harmonic (= fundamental) cyclotron resonance at 110 keV corresponds to a magnetic field strength at the surface of the neutron star of $\sim 1 \times 10^{13}$ G ($\sim 5 \times 10^{12}$ G if the first harmonic is at 55 keV).

Subject headings: gamma rays: observation — line identification — stars: individual (A0535+26) — stars: magnetic fields — stars: neutron — X-rays: stars

1. Introduction

The massive X-ray binary A0535+26 is a recurrent transient pulsar, with pulse period ≈ 104 s (Rosenberg et al. 1975) and recurrence period ≈ 111 days (Motch et al. 1991). The optical companion is the Be star HDE 245770 (Li et al. 1979) at an estimated distance of 1.8 ± 0.3 kpc (Giangrande et al. 1980). For a review, see Giovanelli & Graziati (1992). The X-ray outbursts are thought to be powered by enhanced mass transfer from the companion star near periastron. The intensity of the X-ray emission can vary dramatically from one periastron passage to the next: No outburst may be observed; a "typical" outburst may occur, with peak flux of a few hundred mCrab units (1–10 keV); or a "giant" outburst may occur, with peak X-ray flux of several Crab units. Giant outbursts may appear away from periastron (Motch et al. 1991).

Previous hard X-ray spectra of A0535+26 have been modeled variously as exponential ($kT = 17$ keV; Hameury et al. 1983), blackbody ($kT = 9$ keV; Frontera et al. 1985), and Wien ($kT = 8$ keV; Dal Fiume et al. 1988). Kendziorra et al. (1992, 1994) reported the detection of two absorption features, near 50 keV and 100 keV, in the spectrum of A0535+26 in outburst. Previous estimates of the magnetic field strength have ranged over $4 - 20 \times 10^{12}$ G, based on the suggestion of cyclotron line features (Kendziorra et al. 1992, 1994), the energy dependence of the pulsed fraction (Dal Fiume et al. 1988), or the multiplicity of pulse shapes at low energies (Kanno 1980).

We report here on spectral observations of A0535+26 by the Oriented Scintillation Spectrometer Experiment (OSSE) on the Compton GRO over the interval 1994 February 8–17, during the rise immediately preceding the peak of a giant outburst. These observations were scheduled as a "target of opportunity" triggered by the detection of the outburst by the BATSE instrument on GRO. The rise to maximum of this giant outburst spanned a binary phase interval of $\sim$0.15, with the peak intensity occurring on 1994 February 18 at binary phase 0.95 ± 0.03, according to the ephemeris of Motch et al. (1991). At the maximum, the pulsed emission reached 8 Crab (nebula + pulsar) flux units in the 20–40 keV band (Finger, Wilson, & Hagedon 1994; Wilson et al. 1994).

2. Observations

The OSSE instrument consists of four nearly identical large-area NaI(Tl)–CsI(Na) phoswich detector systems, as described in detail in Johnson et al. (1993). Full-resolution spectra were accumulated every 4.096 s in a sequence of two-minute measurements of the source field alternated with two-minute, offset-pointed measurements of background. The observation was made in twice-normal gain to improve the low-energy response. A total of 1.8×10^5 s of highest-quality data, equally divided between source and background, were collected for each of the four detectors.

For this observation, the source and background fields were placed to ensure that the Crab Nebula, a potentially contaminating source, did not cause a significant contribution to the flux measurement of A0535+26. Below 100 keV, the net (source – background) Crab contribution is <0.1% of the measured flux from A0535+26, and in the critical range from 100–200 keV where we see spectral structure, the contribution is $< 10^{-4}$ photons cm^{-2} s^{-1} MeV^{-1}, or $\lesssim 1\%$ of the measured A0535+26 flux.

3. Results

We detected emission from A0535+26 with high statistical significance from 45 keV to ~200 keV. The average 45–200 keV luminosity during 1994 February 8–17 was $4 \times 10^{36}\,(d/1.8\,\mathrm{kpc})^2$ erg s^{-1}; the luminosity doubled over the nine days of the observation, from 2.5×10^{36} to $5.1 \times 10^{36}\,(d/1.8\,\mathrm{kpc})^2$ erg s^{-1}.

We fit the phase-averaged spectrum between 45 keV and 300 keV from the sum of the four detectors for the entire observation using a forward-folding method (Johnson et al. 1993). We derived error estimates in the parameters of the various spectral models by χ^2-mapping, with confidence intervals specified according to Lampton, Margon, & Bowyer (1976). With such a strong source, it is important to address possible sources of systematic error. We have identified a number of likely contributors, and in all the analysis described herein we have added our best estimate of the systematic error to the statistical error. The systematic error becomes the dominant source of error below $\approx$70 keV, rising to $\sim$3% of the flux at 45 keV. It does not significantly alter the values of the best-fit parameters.

Fig. 1a shows the phase-averaged spectrum summed over the entire observation. The spectrum is quite soft (Wien temperature $\approx$10 keV), although no single-component model adequately describes the spectrum. Simple continuum models show very significant residuals and have unacceptably large χ^2 values (Table 1). The structure apparent above 100 keV could indicate the emergence of weak, underlying, high-energy continuum emission, or it could indicate a broad emission or absorption line. To determine which of these is most likely, we tested a number of models in two classes: a class of two-component continuum spectra, and a class of single-component continuum spectra together with line profiles for emission or absorption (Table 1). In both classes, the continuum model that accounts for the bulk of the emission is a power law times an exponential (hereafter, "PLExp"), chosen because of its general adequacy in describing the standard and hard X-ray spectra of X-ray binaries (White, Swank, & Holt 1983).

The models from the first class, the two-component continuum models, do not give acceptable fits (Table 1). The weak, hard continuum necessary to describe the emission above 100 keV—either a simple power law or PLExp—has a substantial effect on the spectrum below 100 keV and generates significant residuals. Models from the second class employing a Gaussian emission feature (centroid energy $\approx$150 keV) are similarly poor, with

χ^2 probabilities $< 10^{-7}$.

The remaining models from the second class, those with broad absorption lines, provide substantially better fits. In these models, the continuum is modified by a multiplicative transmission function from one or more absorption lines, which we presume arise from cyclotron resonant scattering. First proposed by Tanaka (1986), the transmission function assumes an exponentiated Lorentzian-times-E^2 form, which resembles the cyclotron scattering cross section (Herold 1979; Daugherty & Harding 1986; Harding & Daugherty 1991) and has been used successfully to model cyclotron absorption features in Ginga data (e.g. Nagase et al. 1991; Tamura et al. 1992). The model function has the form

$$f(E) = A\,C(E)\,\exp[-L(E)]\,, \tag{1}$$

where

$$C(E) = E^{-\alpha}\,\exp(-E/kT) \tag{2}$$

and

$$L(E) = \sum_{n=1}^{2} \frac{\tau_n\,(nW)^2\,(E/nE_L)^2}{(E-nE_L)^2+(nW)^2}\,. \tag{3}$$

The continuum term, C(E), is the PLExp model with folding energy kT. In the absorption profile $L(E)$, parameters τ_n, nE_L, and nW are the optical depth, energy, and width (the half-width at half maximum of the Lorentzian, HWHM) of absorption line $n = 1$ or 2. We have assumed a harmonic relationship of 1:2 between the line energies and widths. While in the relativistic treatment the resonant energies are not strict multiples of the cyclotron energy (Herold 1979), the nonlinearities are small (of order several percent for the first few levels) and have been ignored. Trial fits with independent line energies and widths were consistent with the harmonic assumption and did not substantially improve the fit.

Table 1 shows that the best fit is achieved with the general PLExp continuum model with two absorption lines, although the first harmonic (= fundamental) near 55 keV has a small optical depth ($\tau_1 = 0.1^{+0.5}_{-0.1}$; 68% confidence, $\chi^2_{min} + 7.0$), which serves mostly to flatten the model spectrum at low energies. Indeed this absorption line is not strictly required with the PLExp continuum model: χ^2 probabilities for models with free or zero optical depth at 55 keV are both acceptable (33% and 22%, respectively). The 95% confidence upper limit is $\tau < 1.1$ ($\chi^2_{min} + 12.6$). We note also that the Wien continuum with two absorption lines is acceptable; however the lines are extremely broad (42^{+4}_{-3}% HWHM), and the 55 keV line is difficult to distinguish from a smooth change in the continuum.

Parameters of the best-fit model are given in Table 2. The errors given correspond to 68% confidence intervals for six interesting parameters (we judge the intensity A to be irrelevant); thus we use $\chi^2_{min} + 7.0$. Care should be taken in interpreting the error estimates for this non-linear model; for example, the 95% (i.e. "2σ") confidence interval is not given by twice the 68% (i.e. "1σ") confidence interval. The best-fit optical depth of the line at 110^{+2}_{-4} keV is $1.8^{+1.1}_{-0.5}$, implying ~15% transmission at the centroid. The width of the line (28^{+16}_{-9} keV HWHM) is typical of the absorption features detected by Ginga (~ 25%, e.g. Tamura et al. 1992). The width and depth of the line combine to affect the overall spectrum significantly throughout the 45–200 keV band (Fig. 1c). Because of the large uncertainties in the data above 150 keV, the existence of possible higher harmonics near 165 keV and 220 keV is not well constrained; e.g. the 95% confidence upper limit on the optical depth at 165 keV is $\tau < 4$ ($\chi^2_{min} + 14.1$). Fig. 1a shows a PLExp continuum model with a single absorption feature (near 110 keV); the optical depth of the potential first harmonic near 55 keV has been set to zero. With only a single absorption line, significant correlation among the parameters is removed, and the confidence intervals (inset Fig. 1a) are significantly smaller than those in Table 2. The residuals (Fig. 1b) demonstrate that a feature near 55 keV is not required, reinforcing the conclusion drawn from the χ^2 probabilities. The total excess emission above the model in the 200–600 keV band is $<2\sigma$.

We have also employed a more general line profile than that of eqs. 1 and 3, a multiplicative Gaussian. Fits with this symmetric profile are essentially identical in quality to those given above (e.g., for the two-line model $\chi^2_{min} = 1.09$ with 89 degrees of freedom) and lead to identical conclusions, in particular that only the line near 110 keV is strongly required. The line centroid is shifted to a slightly higher energy (115^{+3}_{-4} keV), presumably because the Gaussian lacks the blue tail of the exponentiated Lorentzian-times-E^2. The line width is unchanged (26^{+69}_{-7} keV HWHM), although it is not well constrained. The line width is governed by thermal broadening, as well as the averaging over magnetic field conditions and viewing angle present in the phase-averaged spectrum.

Fits to the spectrum for each day show that the line centroid and width vary by $< 2\sigma$, which suggests that we have not introduced a significant bias by summing the data over the entire observation. However, as the luminosity increases during the outburst, the spectrum does soften. In order to characterize the spectral change in a simple manner, we fit the daily spectra over 45–80 keV with a Wien law. Although formally these fits are only marginally acceptable (χ^2 probabilities typically $\sim 1\%$), they are sufficient to convey that the magnitude of the softening is modest. The Wien temperature decreases by 7% as the luminosity doubles.

4. Discussion

We have shown that an absorption feature near 110 keV is present in the phase-averaged spectrum of A0535+26 during the giant outburst of 1994 February. This is the first time that both the low-energy and high-energy wings of an absorption line have been clearly detected at such high energies in any binary pulsar. We interpret this absorption as a signature of cyclotron resonance scattering. Two-continuum and continuum + emission-line models are strongly rejected by the χ^2 test (Table 1).

We are unable to make a definitive statement on the presence of a 55 keV absorption line in the phase-averaged spectrum. Furthermore, there have been no reports to date on the existence of such a feature in the BATSE data. Adequate fits to the OSSE data are obtained with and without this feature, with a slight preference for a weak line in combination with the general power-law-times-exponential continuum (Table 1). However, we caution that it is always difficult to distinguish between the appearance of a weak, broad line feature and an inadequate description of the underlying continuum: There is significant coupling between the line and continuum model parameters. Such is the case here, and it is compounded by uncertainties in the instrument response and the absence of adequate spectral coverage below the nominal line energy. We can conclude, however, that if a 55 keV feature is present, its optical depth must be significantly smaller than that of the 110 keV feature. It is surprising that the ratio of depths would be small ($\sim$1:20 in the best-fit model with both depths free; $<$1:3.5 at 95% confidence). Radiative transfer calculations based on a neutron-star paradigm for the hard-spectrum γ-ray bursts do show significant filling-in of the first harmonic by two-γ decay of the second excited state (e.g. Wang et al. 1989; Alexander and Mészáros 1991). However, Bulik et al. (1992) point out that this "photon spawning" process should be much less important in accreting X-ray pulsars, where the typically soft, thermal spectrum would not populate the higher harmonics significantly, and therefore would not lead to any appreciable downscattering into the first harmonic.

Kendziorra et al. (1992, 1994) reported the detection of two absorption features ($\approx$50 keV and $\approx$100 keV) in the spectrum of A0535+26 at periastron. An exponentially-truncated power law model for the underlying continuum was required by their combined TTM and HEXE spectrum; a Wien law was unacceptable. The 50-keV absorption was detected at low significance ($\lesssim 3\sigma$) in the phase-averaged spectrum, and HEXE lacked the sensitivity to detect with certainty the high-energy wing of the 100-keV line; however, most importantly, the amplitudes of the absorption features depended on rotation phase. We have begun analysis of the phase-resolved spectroscopy data from OSSE, which will be sensitive to a phase-dependent absorption at 55 keV, if it exists. We note that the 95% confidence limit we set here on the optical depth at 55 keV ($\tau < 1.1$) in the phase-averaged spectrum does not exclude the HEXE value.

If the feature at 110 keV does indeed result from cyclotron resonant scattering in a strongly magnetized plasma, it can be used to estimate the magnetic field strength. A first harmonic resonance at 110 keV corresponds to a field strength at the surface of the neutron star of $9.5 \times 10^{12}\,(1+z)$ G, where z is the gravitational redshift. If instead the first harmonic is at 55 keV, the field is $4.7 \times 10^{12}\,(1+z)$ G. In either case, this is the highest field strength for an accreting neutron star ever measured through direct detection of cyclotron absorption, although the value is within reason and is consistent with the strongest magnetic fields inferred from the spin-down of radio pulsars.

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Description	$\chi^2_{\rm dof}$ (dof)
Single-continuum models	
OTTB[a]	59.4 (94)
Wien	11.7 (94)
PLExp[b]	5.44 (93)
Two-continuum models	
PLExp + Power Law	5.42 (91)
PLExp + PLExp	5.30 (90)
Continuum + emission line models	
Wien + Gaussian	11.9 (91)
PLExp + Gaussian	4.72 (90)
Continuum with absorption models	
Wien × One Line[c]	1.86 (91)
Wien × Two Lines	1.13 (90)
PLExp × One Line[c]	1.11 (90)
PLExp × Two Lines	1.06 (89)

Table 1: Minimum $\chi^2_{\rm dof}$ values for candidate spectral models.

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[a] Optically thin thermal bremsstrahlung.

[b] Power law times exponential.

[c] $E_L \approx 110$ keV.

Continuum Parameters		Line Parameters	
Intensity ($\mathrm{cm}^{-2}\ \mathrm{s}^{-1}\ \mathrm{MeV}^{-1}$)[a]	$2.35^{+4.32}_{-0.35}$[b]	Line Energy, 1st Harm.,[d] E_L (keV)	$55.0^{+1.1}_{-1.9}$
Power Law Index,[c] α	$-0.13^{+0.65}_{-1.67}$	Line HWHM, 1st Harm.,[d] W (keV)	$14.2^{+8.1}_{-4.5}$
Folding Energy, kT (keV)	$17.8^{+5.4}_{-3.8}$	Optical Depth, 1st Harm., τ_1	$0.10^{+0.48}_{-0.10}$
		Optical Depth, 2nd Harm., τ_2	$1.8^{+1.1}_{-0.5}$

Table 2: Best-fit parameters for power-law-times-exponential continuum and two absorption lines.

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[a] At 70 keV.

[b] Errors correspond to 68% confidence, assuming six interesting parameters ($\chi^2_{min} + 7.0$; Lampton, Margon, & Bowyer 1976).

[c] i.e., photon spectral index.

[d] Energy and HWHM of 2nd harmonic are twice those of 1st harmonic.

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Fig. 1.— a) Phase-averaged spectrum of A0535+26 from 1994 February 8–17. The outburst peaked 1994 February 18 (Wilson et al. 1994). Solid line is the model fit, consisting of a power law times an exponential continuum (eq. 2) with transmission function of a single absorption line near 110 keV (eq. 3). Inset shows joint 68% (χ^2_{min}+5.9) and 95% (χ^2_{min}+11.1) confidence intervals for the line centroid and optical depth from the single-line model. b) Residuals from best fit. c) Transmission function for the best-fit absorption line near 110 keV. Data are divided by the continuum portion (eq. 2) of the best-fit model.