OSSE Observations of X-Ray Pulsars

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Abstract

We report on OSSE observations of the Be binary pulsars A0535+26, GRO J1008–57, and 4U 0115+63 at energies above 50 keV. The spectra are generally thermal, with exponential folding energies of 15–25 keV, and no evidence for hard power-law tails. We have clearly detected a strong cyclotron absorption line at 110 keV from A0535+26 [1], and we find a *suggestion* of an absorption line near 90 keV from GRO J1008–57.

Introduction

We report on GRO/OSSE observations of three X-ray pulsars with Be-type stellar companions, namely A0535+26, GRO J1008–57, and 4U 0115+63. Be binary systems are known to be transient hard X-ray emitters, with the increased emission usually interpreted as episodic mass transfer to the neutron star from the Be companion. Outbursts may vary dramatically in intensity from orbit to orbit, and they can last for a significant fraction of the binary period.

A0535+26

The Be binary A0535+26 is a recurrent transient pulsar with pulse period ≈ 104 s and recurrence period ≈ 111 d [2]. OSSE observed A0535+26 over 1994 Feb 8–17, during the rising portion of a giant outburst [1]. We found that the phase-averaged spectrum showed unambiguous evidence for an absorption line at 110 ± 3 keV with optical depth $\tau = 1.8^{+1.1}_{-0.5}$. Because of OSSE's 45 keV threshold, we were unable to make a definitive statement on the presence of a 55 keV absorption line; however we could conclude that its optical depth must be significantly smaller than at 110 keV ($\tau_{55} < 0.3\,\tau_{110}$ at 95% conf.). If the 110 keV feature is due to resonant cyclotron scattering, it implies a magnetic field strength of $9.5 \times 10^{12}\,(1+z)$ G (half this value if the first harmonic is at 55 keV), the highest magnetic field measured by cyclotron absorption [1].

Fig. 1 shows background-subtracted pulse profiles in four energy bands, obtained by folding 4-s rates according to the BATSE ephemeris [3]. At the lowest energies, the pulse profiles show a clear double-peaked structure, with an asymmetric main pulse and a broad secondary pulse. It is apparent from the four pulse profiles, particularly in the secondary peak and the trailing edge of the main peak, that the spectrum is phase dependent. Furthermore, the emission above the 110 keV feature contains a substantial pulsed component (Fig. 1d; Fig. 2). Phase-resolved spectroscopic analysis is in progress.

The energy dependence of the modulated portion of the total emission is shown in Fig. 2. We define the "pulsed fraction" f_p as the ratio of the

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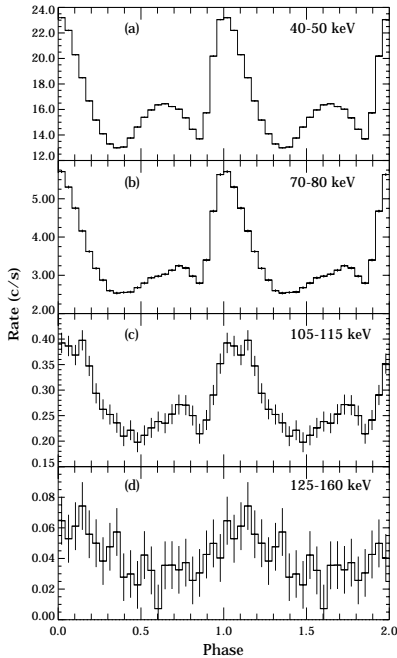| 16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES **4**	19a. NAME OF RESPONSIBLE PERSON
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Figure 1: *Background-subtracted pulse profiles in four energy bands over 1994 Feb 8–17. The profile from a single rotation is duplicated in each panel. We emphasize that the background is estimated for each rate sample before folding; consequently the derived pulse profiles contain only source flux as a function of rotation phase. Note suppressed zero in (a)–(c).*

total modulated component to the total source flux, and the "modulation index" $\phi(E) = 1 - I_{min}(E)/I_{max}(E)$, where I_{min} and I_{max} are respectively the minimum and maximum intensity in each energy band (following [4]). Both measures of the degree of modulation appear to dip to a local minimum at the energy of the cyclotron line. The pulsed fraction varies over $\sim$20–30% between 40 keV and 120 keV, with no obvious features near 55 keV. Our results are in marked contrast with those of [4], which showed $f_p = 100\%$. We attribute this discrepancy to the lower signal-to-noise in their data, as well as
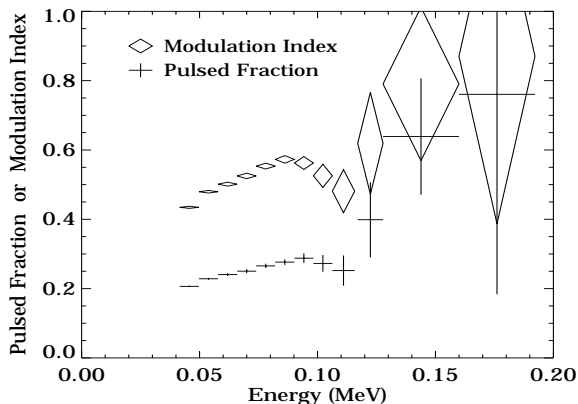

Figure 2: *Pulsed fraction (crosses) and modulation index (diamonds) as a function of energy. See text for definitions.*

a systematic bias toward small values in their definition of I_{min} and thus high values of f_p and ϕ. It has been suggested [5] that the pulsed fraction should converge to unity at the cyclotron resonance energy; however this is clearly not the case for A0535+26.

GRO J1008−57

The transient X-ray pulsar GRO J1008−57 was discovered by BATSE during a large outburst in 1993 July with a pulsation period of 93.86 s [6]. The optical counterpart is consistent with a Be-type star [7]. The binary orbit remains unknown, although a second outburst was detected by BATSE about 260 days after the discovery outburst [8].
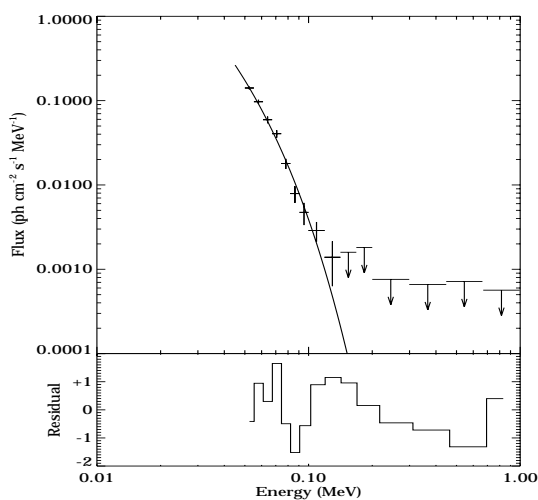
Figure 3: *Spectrum of GRO J1008–57 , fit with thermal bremss. model with kT = 16 ± 2 keV. Residuals (bottom panel, in units of σ) may suggest an absorption feature near 90 keV.*

OSSE observed GRO J1008−57 for ∼7.5 days near the end of the discovery outburst. The first three days were used to locate the source, while the remainder was devoted to spectroscopy above 50 keV. The spectrum is shown in Fig. 3 accumulated over 1993 July 30 − Aug 3 (50–200 keV flux ∼40 mCrab), along with a thermal bremsstrahlung model with $kT = 16 \pm 2$ keV. An F test shows that the addition of an absorption line at 88 ± 5 keV improves the fit at the ∼85% confidence level (i.e. slightly less than 2σ). OSSE is not sensitive to a possible sub-harmonic near 45 keV, and we note that BATSE is not particularly sensitive to lines of moderate optical depth at either energy. Thus we conclude that there is a tantalizing *suggestion* of a high-energy cyclotron absorption feature, which would imply a magnetic field strength of 7×10^{12} G (or half this value). This is worthy of a follow-up observation in a subsequent outburst by OSSE or XTE/HEXTE.

4U 0115+63

The Be binary pulsar 4U 0115+63 has spin period 3.61 s and orbital period

24.3 d [9]. It is quite well studied below $\sim$40 keV, having been detected in at least 10 outbursts. Cyclotron absorption lines at 12.5 keV and 22.6 keV with roughly equal optical depths (0.2 and 0.3, respectively) were detected by Ginga [10,11]. They did not detect higher harmonics; however the spectrum showed an exponential break of $kT = 9.2$ keV from a power law with photon index $\alpha = 0.36$.
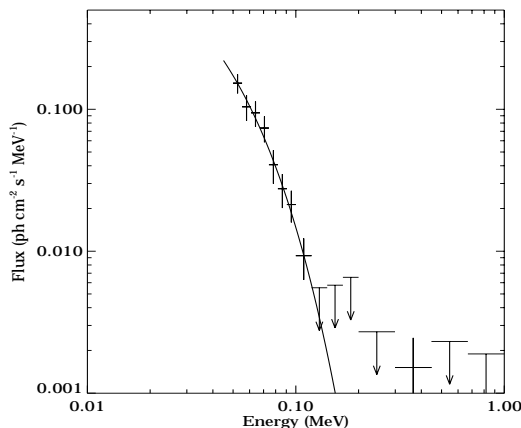

Figure 4: *Spectrum of 4U 0115+63 at peak of outburst, 1994 May 29-31, with exponential folding energy 20 ± 2 keV.*

OSSE observed 4U 0115+63 in four several-day intervals spanning the 1994 May–June outburst, which lasted throughout a full binary orbit. The spectrum from three days at the peak of the outburst is shown in Fig. 4 along with a simple exponential continuum model with folding energy $kT = 20 \pm 2$ keV. Fitting with the Ginga model and fixing $\alpha = 0.36$ gives a folding energy of 18 ± 2 keV; thus the spectrum above 50 keV is somewhat harder than a simple extrapolation from the Ginga spectrum (from a different outburst). The folding energy is highest on the rising portion of the outburst (May 24–28, 24 ± 3 keV) and falls monotonically as the outburst peaks and then decays, reaching 12 ± 3 keV for June 14–18. There is no evidence for high-order cyclotron-absorption harmonics.

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