BATSE SD Observations of Hercules X-1

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The cyclotron line in the spectrum of the accretion-powered pulsar Her X-1 offers an opportunity to assess the ability of the BATSE Spectroscopy Detectors (SDs) to detect lines like those seen in some GRBs. Preliminary analysis of an initial SD pulsar mode observation of Her X-1 indicated a cyclotron line at an energy of \( \approx 44 \) keV, rather than at the expected energy of \( \approx 36 \) keV. Our analysis of four SD pulsar mode observations of Her X-1 made during high-states of its 35 day cycle confirms this result. We consider a number of phenomenological models for the continuum spectrum and the cyclotron line. This ensures that we use the simplest models that adequately describe the data, and that our results are robust. We find modest evidence (significance \( Q \sim 10^{-4}-10^{-2} \)) for a line at \( \approx 44 \) keV in the data of the first observation. Joint fits to the four observations provide stronger evidence \( (Q \sim 10^{-7}-10^{-4}) \) for the line. Such a shift in the cyclotron line energy of an accretion-powered pulsar is unprecedented.

INTRODUCTION

BATSE Spectroscopy Detector (SD) observations of the cyclotron line in the spectrum of the accretion-powered pulsar Hercules X-1 provides an opportunity to assess the capability of the SDs to detect such lines in the spectra of GRBs. Observations of Her X-1 have been performed by many groups \cite{1,2,3}. In particular, analysis of data from the HEAO 1 A4 instrument \cite{4}, which is a NaI detector (like the SDs) and has an effective area and resolution that are similar to a single SD, yields a line center energy \( E = 36 \) keV and equivalent width \( W_E = 8 \) keV. However, preliminary analysis \cite{5} of an initial SD pulsar mode observation of Her X-1 indicated a line at \( \approx 44 \) keV, rather than at the expected energy of 36 keV. We confirm this result by applying rigorous statistical methods developed for analysis of GRB spectra \cite{6} to the analysis of four BATSE SD observations of Her X-1. A companion paper \cite{7} describes studies that have been performed which confirm that the SDs are functioning as expected.
Figure 1. **Left Column:** the pulse-phase spectra for the four BATSE SD observations. We have re-binned the 64 SD phase bins into the 10 phase bins defined by Soong et al., and subtracted counts in order to highlight the pulse. The seven phase bins with the largest number of counts comprise the “On-Pulse” or P phase interval, and the remaining bins comprise the “Off-Pulse” or OP interval; the three phase bins with the largest number of counts comprise the “Peak” interval. **Middle Column:** the P-OP difference spectra. **Right Column:** the Peak-OP difference spectra.
Figure 2. Left Panel: the best-fit model used by Soong et al. to fit the P-OP difference spectrum seen by HEAO 1 A4. Middle Panel: the expected P-OP difference spectrum for an 80 ks observation by a BATSE SD, created by folding the Soong et al. best-fit spectrum through the SD response matrix. Right Panel: the observed P-OP difference spectrum for the 194 ks first observation, 9030-9040.

TABLE 1. Analyzed BATSE SD Observations of Her X-1

| Observation (TJD<sup>a</sup>) | SD | $\theta_{\text{inc}}$ | $t_{\text{obs}}$ (ks) |
|-------------------------------|----|----------------------|----------------------|
| 9030-9040                    | 0  | 19$^\circ$           | 194                  |
| 9447-9461                    | 6  | 8$^\circ$            | 158                  |
| 9482-9488                    | 6  | 23$^\circ$           | 93                   |
| 9937-9944                    | 1  | 24$^\circ$           | 161                  |

<sup>a</sup> Truncated Julian Date

ANALYSIS

In Table 1 we list the four highest quality SD observations of Her X-1 made to date; these observations were undertaken during high-states of the Her X-1 35 d cycle. Figure 1 shows the SD pulse-phase data rebinned into the 10 phase bins defined by Soong et al., and the “On-Pulse” minus “Off-Pulse” (P-OP) and the “Peak” minus “Off-Pulse” (Peak-OP) difference spectra. We analyze the P-OP difference spectra and, to improve S/N, the Peak-OP difference spectra. During the observations, the Low Level Discriminator (LLD) was set to $\approx 10$ keV. Because of non-linearities in the energy-to-channel conversion within $\approx 10$ keV of the energy of the LLD, we fit only to energy-loss bins above 20 keV.

Soong et al. fit the spectrum of Her X-1 using a continuum model which is a power law up to a break energy, and an exponential above this energy times a Gaussian line (Figure 2). The count spectrum seen by BATSE differs in three ways from that expected from folding the best-fit Soong et al. spectrum through the SD response matrix and adding simulated noise: the break energy of the observed spectrum is $\approx 10$ keV higher than expected, the slope of the observed spectrum above the break is greater than expected, and the observed spectrum does not show the expected plateau around $\approx 36$ keV (Figure 3).

Because the observed spectra differ from that expected, we investigate not only the Soong et al. continuum model, but other continuum models as well. We seek the simplest model that adequately fits the data. We use a statistical
TABLE 2. Analysis of Single Observations: Peak Phase Interval

| Obs. (TJD) | Soong       | BPL       |
|-----------|-------------|-----------|
|           | E (keV)     | W_E (keV) | Q     | E (keV)     | W_E (keV) | Q     |
| 9030-9040 | 44.0        | 7.5       | 2.5x10^{-4} | 44.3 | 6.1       | 8.7x10^{-3} |
| 9447-9461 | No Improvement in $\chi^2$ | No Improvement in $\chi^2$ |
| 9482-9488 | 40.5        | 1.9       | 0.50  | No Improvement in $\chi^2$ |
| 9937-9944 | 42.8        | 5.6       | 0.013 | 43.6 | 4.4       | 0.068 |

criterion based on the maximum likelihood ratio (MLR) test[7][10]. Use of this criterion often leads to the selection of a broken power law (BPL) model for the continuum, rather than the Soong et al. model. Joint fits indicate that this preference becomes stronger as we include the data from additional observations. The preference for the BPL over the Soong et al. model may be a consequence of the fact that we are unable to include data below 20 keV. Because the line lies on the steeply-falling part of the Her X-1 spectrum, there can be a large difference between the values of the Soong et al. and BPL continuum models at the line, and therefore in the significance of the line. We therefore give the results of continuum-plus-line fits to the data using both the Soong et al. and BPL continuum models.

We use an exponentiated Gaussian absorption model to fit the line. In this model, the line full-width at half-maximum $W_{\text{FWHM}} = \eta W_E$, and $\eta \approx 1$ represents a saturated line. Using a procedure analogous to the one that we use to select continuum models, we select the simplest continuum-plus-line model that adequately fits the data. We find that a one-parameter saturated line model in which we fix the line center energy at $\approx 36$ keV never leads to a reduction in $\chi^2$ from the best continuum fit. We find that a two-parameter saturated line model adequately fits all of the data. We use the MLR test to determine the significance of the line.

In fits to the P-OP difference spectra, we find no evidence for a line in any of the four individual SD observations. The largest line significance ($Q = 0.18$) occurs for the first observation. Fits to simulated SD data created using the best-fit Soong et al. model for the Her X-1 spectrum, but with the line energy shifted to $\approx 43$ keV, show that this result is not inconsistent with a line at $\approx 43$ keV. Using joint fits, we find that the largest line significance ($Q = 0.05$) occurs when we combine data from the first and fourth observations.

In fits to the Peak-OP difference spectra, we detect a line at $\approx 44$ keV with modest significance in the data from the first observation (Table 2), but not in the data from any other observation. Joint fits indicate that this line becomes more significant as we add the data from more observations.

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1 This test assumes that the difference $\Delta \chi^2$ resulting from two model fits to data is distributed like $\chi^2$ for $N$ degrees of freedom, where $N$ is the number of additional parameters in the more complicated of the two models. $Q$ is the area under this distribution for $\chi^2 > \Delta \chi^2$, and small $Q$ values indicate that it is unlikely that the improvement $\Delta \chi^2$ between the two fits would occur by chance.
TABLE 3. Analysis of Joint Observations: Peak Phase Interval

| Obs. (TJD) | Soong | BPL |
|-----------|-------|-----|
|           | $E$ (keV) | $W_E$ (keV) | $Q$ | $E$ (keV) | $W_E$ (keV) | $Q$ |
| 9030      | 44.0   | 7.5  | $2.5 \times 10^{-4}$ | 44.3 | 6.1  | $8.7 \times 10^{-3}$ |
| 9030/9937 | 43.6   | 6.7  | $4.7 \times 10^{-7}$ | 44.1 | 5.4  | $9.8 \times 10^{-5}$ |
| All - 9482| 43.8   | 6.7  | $3.2 \times 10^{-7}$ | 44.1 | 5.3  | $8.8 \times 10^{-5}$ |
| All       | 43.1   | 5.3  | $2.3 \times 10^{-6}$ | 43.5 | 3.9  | $4.6 \times 10^{-4}$ |
| 9447/9937 | 43.7   | 5.6  | $0.010$             | 44.9 | 4.8  | $0.054$     |
| All - 9030| 41.1   | 2.1  | $0.21$              | No Improvement in $\chi^2$ |

(Table 3). However, the addition of data from the third observation reduces the significance of the line. This behavior may reflect the fact that each of the four observations covers a slightly different phase of the Her X-1 35 d cycle. If we exclude the first observation from the joint fits, we find that we cannot detect the line.

We estimate the statistical error for each model parameter using Monte Carlo simulations of the best-fit models. The typical 1σ uncertainties for both $E$ and $W_E$ are $\approx 1.0$-$1.5$ keV.

CONCLUSIONS

Joint fits to four SD observations of Her X-1 show strong evidence for a cyclotron scattering line at $\approx 44$ keV, rather than at the expected energy of 36 keV. A cyclotron line energy shift is unprecedented in observations of accretion-powered pulsars. A companion paper (8) describes studies that have been conducted which confirm that the SDs are functioning as expected.

REFERENCES

1. J. Trümper, W. Pietsch, C. Reppin, W. Voges, R. Staubert, and E. Kendizor, Ap. J. 219, L105 (1978).
2. D. E. Gruber, et al., Ap. J. 240, L127 (1982).
3. W. Voges, W. Pietsch, C. Reppin, J. Trümper, E. Kendizor, and R. Staubert, Ap. J. 263, 803 (1982).
4. Y. Soong, et al., Ap. J. 348, 641 (1990).
5. T. Mihara, K. Makashima, T. Ohashi, T. Sakao, and M. Tashiro, Nature 335, 234 (1990).
6. D. M. Palmer, et al., Gamma-Ray Bursts, eds. G. J. Fishman, J. J. Brainerd, and K. Hurley (New York: AIP, 1994), p. 247.
7. P. E. Freeman, et al., Ap. J., submitted.
8. W. S. Paciesas, et al., these proceedings.
9. D. Band, et al., Exp. Astr. 2, 307 (1992).
10. W. T. Eadie, D. Drijard, F. E. James, M. Roos, and B. Sadoulet, Statistical Methods in Experimental Physics (Amsterdam: North Holland, 1971).