1978ApJ...219L.105T

THE ASTROPHYSICAL JOURNAL, 219:L105–L110, 1978 February 1
© 1978. The American Astronomical Society. All rights reserved. Printed in U.S.A.

EVIDENCE FOR STRONG CYCLOTRON LINE EMISSION IN THE HARD X-RAY SPECTRUM OF HERCULES X-1

J. TRÜMPER, W. PIETSCH, C. REPPIN, AND W. VOGES
Max-Planck-Institut für Physik und Astrophysik, Institut für extraterrestrische Physik, Munich
AND
R. STAUBERT AND E. KENDZIORRA
Astronomisches Institut der Universität Tübingen
Received 1977 August 19; accepted 1977 October 12

ABSTRACT

We present further results of our Hercules X-1 balloon observation on 1976 May 3 which confirm the existence of a strong line feature at $\sim$58 keV in the pulsed (1.24 s) X-ray spectrum we reported earlier. The spectral excess in the line region over the extrapolated continuum is 5–6 σ. Our best estimates of the line flux and line width are 3×10^{-3} photons cm^{-2} s^{-1} and less than $\sim$12 keV, respectively. The most likely interpretation of this line is electron cyclotron emission at the basic frequency from the hot polar plasma of the rotating neutron star. The corresponding magnetic field strength is 5.3×10^{12} gauss. We have searched for the second-harmonic cyclotron emission line in that part of our data showing the highest signal-to-noise ratio and find a 3.3 σ spectral enhancement near the predicted energy (110 keV). We discuss implications of the line width and the line intensity ratio for the physical conditions of the emitting plasma and the beaming geometry.

Subject headings: magnetic fields — stars: neutron — X-rays: sources — X-rays: spectra

I. INTRODUCTION

In a recent publication (Trümper *et al.* 1977, hereafter Paper I), we reported evidence for a strong and narrow line feature at $\sim$58 keV in the pulsed (1.24 s) X-ray flux from Her X-1. We explained this line as quantized electron cyclotron emission, originating from the hot and highly magnetized plasma at the magnetic poles of the rotating neutron star. If correct, this interpretation has far-reaching implications for the understanding of neutron-star physics. It provides the first measurement of a neutron-star magnetic field, which is the key quantity for all surface and magnetospheric phenomena of these objects. In particular, cyclotron line spectroscopy may become a powerful diagnostic tool for studies of the X-ray emission and beaming processes.

Our balloon observation on 1976 May 3, contained the first detection of the 1.24 s pulses in the 30–88 keV range, and the fact that the 58 keV line appears as a pulsed feature indicates that we are dealing with a genuine source effect.

Recently, a time-averaged spectrum of Her X-1 was taken by *Ariel 5* (Coe *et al.* 1977) which shows some spectral excess consistent with the presence of a line at 64 $\pm$ 6 keV.

Line energy, intensity, and width, presented in Paper I, were based on a preliminary data analysis. The purpose of this *Letter* is to report the results of our final data analysis, which fully confirm Paper I. Furthermore, we have searched for the second-harmonic cyclotron line and provide evidence of its detection.

II. OBSERVATIONS

Her X-1 was observed on 1976 May 3, from 0612 to 1012 UT during a 10 hour balloon flight from Palestine, Texas. The rest of the time was devoted to studies of Cyg X-1, Cyg X-3, and Cyg X-2. The magnetometer-stabilized balloon gondola carried two collimated NaI scintillation counters which were oriented in parallel. Scan and on/off source measurements were performed on telecommand. Energies and arrival times of individual photons were recorded. Table 1 gives an instrument summary.

TABLE 1

INSTRUMENT SUMMARY

	Telescope 1	Telescope 2
Energy range (keV)	15–135	17–160
Effective area (cm^2)	107	87
FWHM energy resolution at 60 keV (keV)	13.2	17.4
Collimators	2° (R.A.) $\times$ 10° (decl.)	

The spectra described in this *Letter* are entirely based on data from telescope 1 (Reppin, Pietsch, and Sacco 1978). The spectral data of telescope 2 exhibit only a (2–3 σ) shoulder on the continuum instead of a line. This difference can be explained by the inferior detector characteristics.

Her X-1 was at binary phase 0.72–0.82 and 5 days after turn-on of cycle 45 (Davison and Fabian 1977) of its 35 day variation. In flight, energy calibration was provided by a ^{241}Am source ($E = 59.5$ keV) which could be exposed by telecommand. We can exclude the possibility that the Her X-1 line was produced by a spurious effect. During the observations the calibration source was well shielded, and we can not detect any ^{241}Am leakage flux in the background spectra. Since

© American Astronomical Society • Provided by the NASA Astrophysics Data System

1978ApJ...219L.105T

brass collimators were used and no material with high atomic number was in the vicinity of the scintillation counters, the Her X-1 line cannot be produced by Her X-1–induced fluorescence radiation in the detector system. This is confirmed by the nonexistence of any line in the Cyg X-1 spectrum measured during the same flight (see Fig. 1*c*).

The Her X-1 observation consisted of a number of pointings interrupted by off-source background measurements. The signal-to-noise ratio of the Her X-1 data decreased during the 4 hours for two reasons. (1) After ~1.5 hours, Her X-1 underwent a flux decrease by a factor of ~3 and stayed at lower intensity for the rest of the time. (2) The non–X-ray background of telescope 1 increased after ~45 minutes by 20% to 30%, depending on energy, owing to a change of observation mode by telecommand. In this *Letter* we report results from the first 45 minutes for which the signal-to-noise ratio of the data was highest.

III. RESULTS

The heliocentric pulsational period of Her X-1 obtained from our data is 1.237803 ± 0.000003 s, and we folded the counts of each energy channel modulo this period into 40 bins. The resulting pulse profiles, which have been discussed separately (Kendziorra *et al.* 1977), are characterized by a single peak structure in the 30–60 keV band and a double peak structure beyond ~60 keV. In the following we use two types of spectra derived from these data: (1) Her X-1 pulse minus Her X-1 off-pulse spectrum (P − OP), defined as the difference of count rate in a 10 bin wide phase interval around the pulse maximum of the 1.24 s period and the count rate in a 23 bin wide interval between the pulses (in Paper I we used 17 bins: 23 bins in order to define the "pulsed spectrum"); and (2) Her X-1 pulse minus off-source spectrum (P − OS), where the pulse count rate is defined as above and the background subtracted is determined from off-source pointings.

Figures 1*a* and 1*b* show the corresponding count rate spectra of telescope 1, which both show clear peaks at ~58 keV and a second enhancement at ~110 keV. We first fitted power-law and exponential spectra to the data, allowing for atmospheric absorption, detection efficiency, energy resolution, and K-iodine escape:

$$I = I_p \times E^{-\gamma} \qquad (\text{photons cm}^{-2}\,\text{s}^{-1}\,\text{keV}^{-1})$$

$$I = I_B \times \frac{1}{E} \exp\left(-\frac{E}{kT}\right) \quad (\text{photons cm}^{-2}\,\text{s}^{-1}\,\text{keV}^{-1})\,.$$

The parameters derived from these χ^2 fits including the resulting $\chi^2_{\min}$ and the significances α_{obs} are summarized in Table 2. According to Lampton, Margon, and Bowyer (1976), the requirement for an acceptable fit is $\alpha_{\text{obs}} \gtrsim 10\%$. It is clear that all two-parameter fits through all data points are not acceptable. The excesses over the continua in the line region (46–75 keV) have all statistical significances of 4 to 5 σ. On the other hand, the data below 46 keV are well fitted by an exponential spectrum. The corresponding excesses over the extrapolated continua in the line region are greater than 5 σ. In order to account for this excess flux we added a power-law tail or, alternatively, a Gaussian line profile to the exponential spectrum:

$$I = \frac{I_B}{E} \exp(-E/kT) + I_p E^{-\gamma}$$

$$I = \frac{I_B}{E} \exp(-E/kT) + \frac{I_L}{\sigma\sqrt{(2\pi)}} \exp\left[-\frac{(E-E_L)^2}{2\sigma^2}\right].$$

The results of these four- and five-parameter fits to *all data points* are given in Table 2 as well. It turns out that for both observed spectra the spectral structure at $E > 46$ keV cannot adequately be described by a power-law tail. On the other hand, the addition of a single Gaussian line profile leads to acceptable fits. This is particularly true for the P − OS spectrum. In the case of the P − OP spectrum, the significance is a little less than required for a good fit; this is mainly due to the apparent narrowness of the line feature in this data set.

Finally, we have made seven-parameter fits (exponential spectrum plus Gaussian lines to both spectra). In the case of the P − OP spectrum the significance remains at 5%, while it becomes 50% for the P − OS spectrum.

The limits quoted in Table 2 are for a joint 68% confidence region in parameter space (see Lampton *et al.*). For the five-parameter fits this corresponds to $\chi^2_{\min} + 5.9$. We note that this leads to considerably larger limits than the usual method of subtracting the best fitting continuum and considering a two- or three-parameter fit to the residual. Applying this procedure, we have made a three-parameter error estimation. The results are also listed in Table 2.

Summarizing, we find strong evidence for the existence of a spectral feature, at 58 ± 5 keV, which has an intensity of 3×10^{-3} cm^{-2} s^{-1}. The best estimate of the line width is at most ~12 keV.

Both spectra displayed in Figures 1*a* and 1*b* show enhancements in several spectral bins around ~110 keV. The statistical significance of the total flux above zero in this energy band is 2.2 σ for the P − OP spectrum and 3.3 σ for the P − OS spectrum. A Gaussian line profile fitted to these points in the P − OS spectrum yields a line energy of 110.6 keV and an intensity of $\sim 2.6 \times 10^{-3}$ cm^{-2} s^{-1} (P − OP: 108 keV, 1.4×10^{-3} cm^{-2} s^{-1}). It is intriguing that this spectral enhancement occurs at just that energy where one expects the second harmonic of an 58 keV line (see below).

Finally, in Figure 2 we show the deconvoluted spectrum of the Her X-1 pulses, which has been obtained from the P − OS spectrum by using an exponential plus Gaussian line fit. For comparison, we have included the total intensity spectrum measured by OSO-8 (Becker *et al.* 1977). There is very good agreement in spectral slope between 20 and 45 keV, where the data overlap. The agreement in absolute intensity seems accidental in view of the variability of the source. Furthermore, our *pulse* spectrum has to be multiplied by a factor ~1.7 in order to make it directly comparable with a *total* spectrum.

© American Astronomical Society • Provided by the NASA Astrophysics Data System

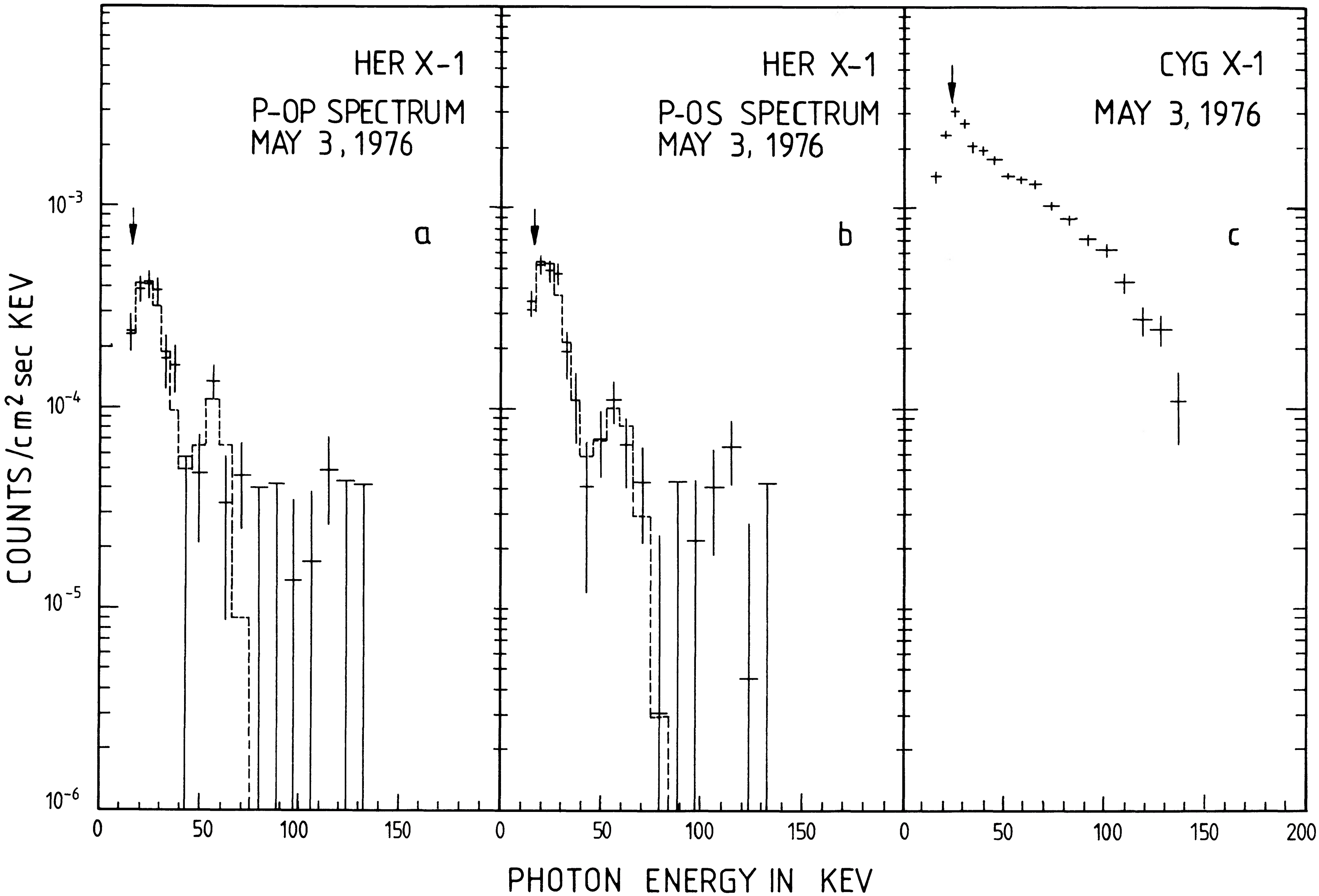

FIG. 1.—Count rate spectra. (*a*) Her X-1 pulse minus off-pulse spectrum. (*b*) Her X-1 pulse minus off-source spectrum. (*c*) Cyg X-1 minus off-source spectrum obtained during the same balloon flight. The error bars are $\pm 1\ \sigma$, the upper limits are at $2\ \sigma$. *Arrows*, low-energy cutoff caused by atmospheric absorption. *Dashed lines*, the best-fitting exponential spectrum with a Gaussian line as described in the text and Table 2. The spectral peaks at 58 keV represent evidence for the cyclotron emission line. The spectral enhancement at ~110 keV suggests emission at the second harmonic.

© American Astronomical Society • Provided by the NASA Astrophysics Data System

1978ApJ...219L.105T

TABLE 2

HERCULES X-1 SPECTRAL PARAMETERS
($E \geq 20$ keV)

Count Rate Spectrum	Fitted Spectrum	p*	$(N-p)$†	$\chi^2_{\min}$	α_{obs} (%)‡	I_B	kT (keV)	I_p	γ	Line Excess (46–75 keV)
P−OP	Power law, all spectral points..	2	16	39.1	0.1	...	...	557	−3.96	4.1 σ
P−OS				34.6	0.4	...	...	1633	−4.22	3.7 σ
P−OP	Exponential, all spectral points	2	16	45.4	<0.1	0.66	9.3	...	...	5.2 σ
P−OS				40.5	<0.1	1.25	8.06	...	...	5.0 σ
P−OP	Exponential, up to 46 keV.....	2	5	8.1	15	1.17	7.65	...	...	>5 σ§
P−OS				4.0	55	2.00	6.96	...	...	>5 σ§
P−OP	Exponential + power-law tail..	4	14	26.2	2.3	3.7	5.6	51.4	−1.6	
P−OS				35.5	0.1	1.9	6.2	135.4	−1.9	

Count Rate Spectrum	Fitted Spectrum	p*	$(N-p)$†	$\chi^2_{\min}$	α_{obs} %‡	I_B	kT (keV)	Line Parameters: Energy (keV)	Line Parameters: Width (keV), FWHM)	Line Parameters: Intensity (10^{-3} cm^{-2} s^{-1})
P−OP	Exponential + Gaussian line profile..........	5	13	22.4	5.0	1.3 (+2.4, −0.8)	7.3 (+2.4, −3.8)	57.5 (+5.5, −3.4)	0(+24.5,0)	2.9 (+3.6, −1.2)
P−OP	Same, 3-parameter error estimation..........	3	...	...	...	...	...	57.5 (+3.9, −3.8)	0(+15.9,0)	2.9 (+3.0, −1.0)
P−OS	Exponential + Gaussian line profile..........	5	13	18.9	13	2.3 (+3.5, −1.2)	6.7 (+1.9, −1.4)	58.5 (+5.2, −5.0)	11.2 (+26.4,−11.2)	3.4 (+2.0, −1.7)
P−OS	Same, 3-parameter error estimation..........	3	...	...	...	...	...	57.5 (+5.9, −5.0)	11.2 (+16.3,−11.2)	3.4 (+1.5, −1.3)

* Number of adjustable parameters.
† Degrees of freedom.
‡ Significance of the fit (see, e.g. Lampton *et al.* 1976).
§ Above extrapolated continuum.

IV. DISCUSSION

It seems impossible to explain a 58 keV line by atomic or nuclear emission for intensity reasons (Paper I). The most likely interpretation appears to be in terms of an electron cyclotron emission line which has been predicted to occur in the X-ray spectra of binary neutron stars by Gnedin and Sunyaev (1974) and Basco and Sunyaev (1975). The Landau levels of an electron in a homogeneous field are given by (see Canuto and Ventura 1977):

$$E_{j,s} = mc^2\left\{\left[1 + \left(\frac{p_z}{mc}\right)^2 + (2j + s + 1)\frac{B}{B_{cr}}\right]^{1/2} - 1\right\},$$

where $j = 0, 1, 2 \ldots$ and $s = \pm 1$ are angular momentum and spin quantum numbers, respectively; B is the magnetic field strength; $B_{cr} = (m^2c^3)/eh = 44.14 \times 10^{12}$ gauss; m is the electron mass; and p_z is the electron momentum along the magnetic field lines. It is likely that the 58 keV line is produced by transitions from the first excited state ($j = 1, s = -1$ or $j = 0, s = +1$) to the ground state ($j = 0, s = -1$). Neglecting the longitudinal motion, we then get $B = 5.3 \times 10^{12}$ gauss. The second harmonic should appear at 110.7 keV (transitions from $2j + s = 3$ to the ground state), which is very close to the energy where the second enhancement (Figs. 1*a*, 1*b*, 2) is observed.

It is generally accepted that the hard X-ray emission originates close to the stellar surface. Correcting for the corresponding gravitational redshift, which is of the order of 10%–40% (Börner 1973; Brecher 1977), we get values between 5.8 and 7.3×10^{12} gauss for the intrinsic polar field strength.

We stress that, on the basis of our experimental data alone, the interpretation in terms of line emission is not conclusive. There could be a cyclotron absorption line at ~42 keV (and a possible second one at ~80 keV). In this case the polar magnetic field strength would be $\sim 4 \times 10^{+12}$ gauss. However, there are convincing theoretical arguments (Basco and Sunyaev 1975) which favor an emission-line explanation.

Accepting the 58 keV feature as an emission line, we can draw some conclusions from the estimated intrinsic line width (less than or approximately 12 keV FWHM): the Assuming a magnetic dipole field, the radial extent of line-emitting region is limited to $\Delta r/r = 1/3 \times \Delta B/B = 0.07$, or, with a neutron-star radius of 10 km, $\Delta r < 700$ meters. (2) A discussion of Doppler (Paper I) and self-

© American Astronomical Society • Provided by the NASA Astrophysics Data System

1978ApJ...219L.105T

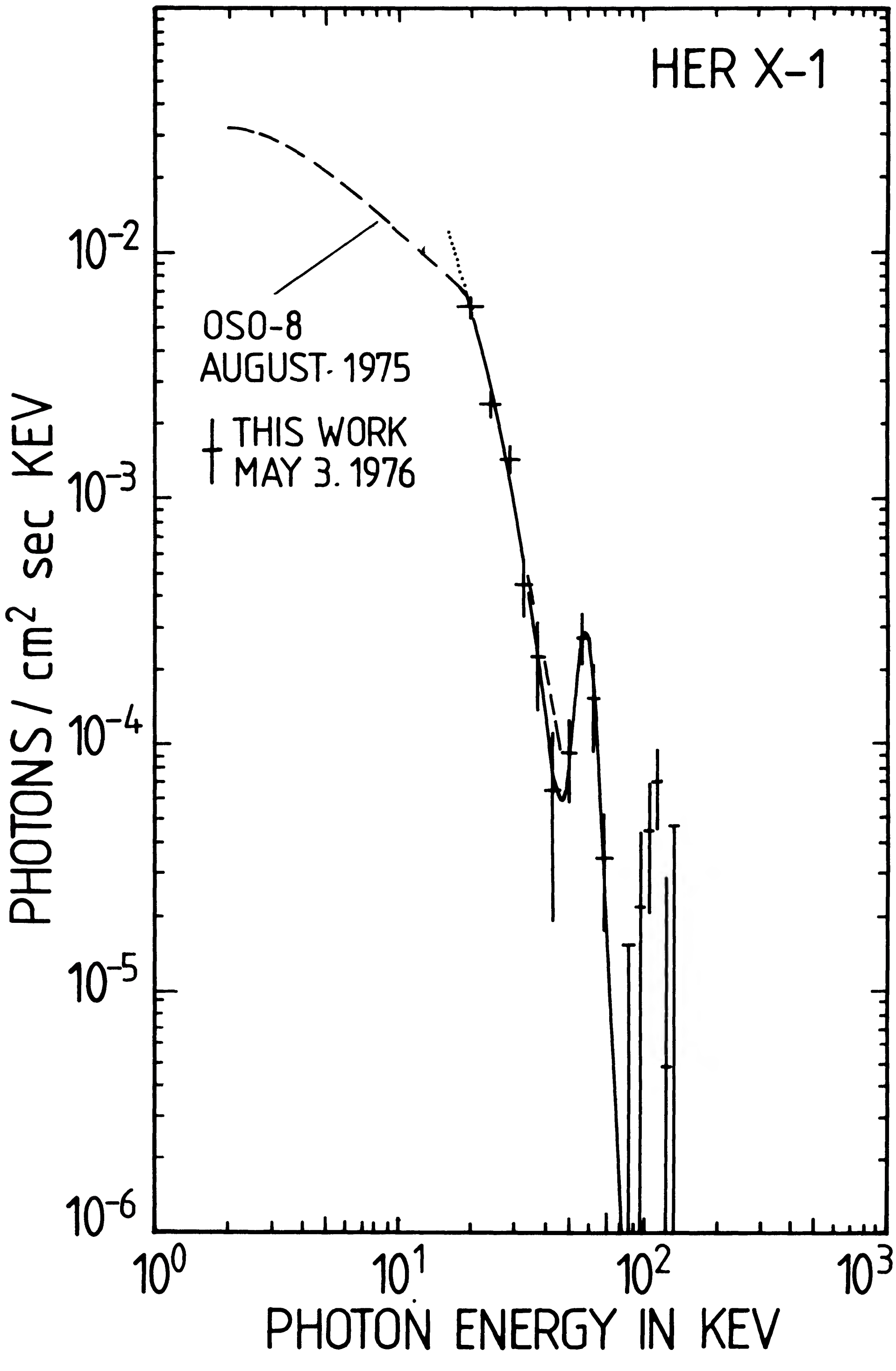

FIG. 2.—Deconvoluted X-ray spectrum of the Her X-1 *pulses*. *Solid line*, best-fitting exponential spectrum with a Gaussian line to the data points. The error bars are $\pm 1\ \sigma$; the upper limits are at $2\ \sigma$. For comparison, a *total* X-ray spectrum of Her X-1 observed by OSO-8 during the 1975 August on-state is shown (Becker *et al.* 1977).

© American Astronomical Society • Provided by the NASA Astrophysics Data System

1978ApJ...219L.105T

absorption line broadening (Mészáros 1977), which both depend on the polar angle of emission, suggests that the radiation pattern is of the fan beam type.

We acknowledge the excellent support by the NCAR staff in Palestine, Texas. This work was funded in part by the Deutsche Forschungsgemeinschaft under grants Tr 11/14 and Tr 11/15. B. Sacco contributed much to the early phases of our data analysis.

REFERENCES

Basco, M. M., and Sunyaev, R. A. 1975, *Astr. Ap.*, **42**, 311.
Becker, R. H., Boldt, E. A., Holt, S. S., Pravdo, S. H., Rothschild, R. E., Serlemitsos, P. J., Smith, B. W., and Swank, J. H. 1977, *Ap. J.*, **214**, 879.
Börner, G. 1973, *Springer Tracts in Modern Physics*, **69**, p. 1.
Brecher, K. 1977, *Ap. J.* (*Letters*), **215**, L17.
Canuto, V., and Ventura, J. 1977, *Quantizing Magnetic Fields in Astrophysics: Fundamentals of Cosmic Physics*, in press.
Coe, M. J., Engel, A. R., Quenby, J. J., and Dyer, C. S. 1977, *Nature*, **268**, 508.
Davison, P. J. N., and Fabian, A. G. 1977, *M.N.R.A.S.*, **178**, 1P.
Gnedin, Yu. N., and Sunyaev, R. A. 1974, *Astr. Ap.*, **36**, 379.
Kendziorra, E., Staubert, R., Pietsch, W., Reppin, C., Sacco, B., and Trümper, J. 1977, *Ap. J.* (*Letters*), **217**, L93.
Lampton, M., Margon, B., and Bowyer, S. 1976, *Ap. J.*, **208**, 177.
Mészáros, P. 1977, preprint.
Reppin, C., Pietsch, W., and Sacco, B. 1978, in preparation.
Trümper, J., Pietsch, W., Reppin, C., Sacco, B., Kendziorra, E., and Staubert, R. 1977, *8th Texas Symposium on Relativistic Astrophysics* (Boston, 1976) (*Ann. NY Acad. Sci.*), in press (Paper I).

E. Kendziorra and R. Staubert: Astronomisches Institut der Universität Tübingen, D-7400 Tübingen, Germany

W. Pietsch, C. Reppin, J. Trümper, and W. Voges: Max-Planck-Institut für Physik und Astrophysik, Institut für extraterrestrische Physik, D-8046 Garching bei München, Germany

© American Astronomical Society • Provided by the NASA Astrophysics Data System