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CYCLOTRON LINES IN THE HARD X-RAY SPECTRUM OF HERCULES X-1

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ABSTRACT

The hard X-ray spectrum of Hercules X-1 in the energy range 26–120 keV was measured during a 4.4 hr balloon observation on 1977 September 3 with a large phoswich detector system. The spectral feature in the 1.24 s pulsations found by us in a 1976 observation and interpreted as electron cyclotron line emission or absorption was detected again and confirmed with large significance (>10 σ). The line feature is located either at ~ 52 keV (as an emission line) or at ~ 38 keV (as an absorption line). This corresponds to a magnetic field strength of $3–5 \times 10^{12}$ gauss. In an emission line model the best value for the line intensity is 2.7×10^{-3} photons cm^{-2} s^{-1}. The line is resolved and has an intrinsic width of ~ 21 keV FWHM, while in an absorption line model the line width appears to be smaller. A search for a possible second harmonic line gave a 2 σ upper limit of 2.4×10^{-4} photons cm^{-2} s^{-1}. An analysis of phase-dependent spectra shows a significant variation of the emission line centroid of the cyclotron feature during the main pulse.

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

I. INTRODUCTION

The compact X-ray source Her X-1, which shows 1.24 s pulsations, a 1.7 day eclipse period, and a 35 day quasi-periodic variation, was first discovered by Tananbaum *et al.* (1972). Subsequently the optical stellar companion HZ Her was identified by Liller (1972) and Bahcall and Bahcall (1972). A summary of the numerous X-ray observations performed at medium (2–30 keV) and soft (<2 keV) X-ray energies can be found in Joss *et al.* (1977). At hard X-rays ($E > 30$ keV) the Her X-1 pulsations were first measured during our balloon flight in 1976 May (Kendziorra *et al.* 1977; Trümper *et al.* 1977, 1978). These observations revealed the existence of a rather sharp spectral feature at ~ 58 keV and possibly a second one at ~ 110 keV. These features were interpreted in terms of electron cyclotron resonance effects occurring in the hot polar plasma located near the surface of the matter-accreting neutron star. The corresponding magnetic field strength is $3–5 \times 10^{12}$ gauss, depending on whether the resonance is seen in emission or absorption. If the interpretation is correct, this observation represents the first direct measurement of a neutron star magnetic field.

In 1977 September we performed a series of balloon flights using a scintillation detector system enlarged by a factor of 6.5 compared with the 1976 observation to further investigate the spectral features of Her X-1. Preliminary data of this observation have been presented in a number of papers (Trümper 1978, 1979, 1982; Voges *et al.* 1979). However, the final analysis was completed only recently, and in this paper we present the results which essentially confirm the earlier findings. A number of groups have reported either independent confirmations (Gruber *et al.* 1980; Scheepmaker *et al.* 1981) or data which are largely consistent with our results within statistical and systematic uncertainties (Evans, Quenby, and Engel 1980; Maurer *et al.* 1979; Pravdo, Bussard, and White 1979; Pravdo *et al.* 1979; Tueller *et al.* 1981, Ubertini *et al.* 1981). Recently, a summary of the observational evidence for a line feature has been given by Staubert *et al.* (1981).

II. OBSERVATIONS

In autumn of 1977 a series of three balloon flights was conducted at Palestine, Texas, to observe Her X-1 at three different phases of its 35^d ON-OFF cycle. In this paper we report the final spectral results from data obtained during the 1977 September 3 observation, when Her X-1 was in its 35^d high-intensity ON state. Table 1 summarizes the phase values of the different source periodicities of Her X-1 for the time of the observation.

The detector system and gondola, as described in detail by Reppin *et al.* (1978), consisted of four phoswich detectors [3 mm thick NaI(Tl) crystals and 50 mm

TABLE 1

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Date	1977 September 3
Time (UT)	21:32–25:56
$1^{d}7$ binary phase[a]	0.13–0.24
$1^{d}6$ absorption dip phase[b]	0.44–0.55
35^{d} ON-OFF cycle[c]	0.12

[a] Calculated by using $P_{\rm orb} = 1^{d}.70016779$ (Deeter, Boynton, and Pravdo 1981) and phase $\phi = 0$ at t_x (time of the center of eclipse of the neutron star) = JD 2,443,357.8711 (1977 Aug 2.3711 UT) (Joss *et al.* 1980).

[b] Calculated by using $P_{\rm dip} = 1^{d}.65964$ and phase $\phi_{\rm dip} = 0$ at $t_{\rm dip}$ (time of leading edge of absorption dip) = JD 2,441,505.97 (Chester 1977).

[c] Calculated by using $P_{35} = 34^{d}.875$ (Holt *et al.* 1979) and phase $\phi_{35} = 0$ at turn on time t_{35} = JD 2,443,386.27 (Pravdo *et al.* 1977).

thick CsI(Tl) shielding crystals]. A brass collimator was incorporated defining a circular field of view of 3° FWHM. The detector effective area was 664 cm^2. Additional background reduction was achieved by a passive graded shield (Pb, Sn, Cu) and an active plastic scintillator anticoincidence. For each individual photon the energy (64 channels between 10 and 200 keV),. the arrival time (< 6.4 ms resolution) and the pulse rise time were recorded. Energy calibration was performed automatically every 30 minutes during the flight, using ^{109}Cd radioactive sources. The energy resolution at 60 keV was 22% FWHM as determined from these measurements and preflight calibration using the radioactive source ^{241}Am. During the Her X-1 observation of 4.4 hours the absolute detector gain was stable to within ±2%. Interpolation between in-flight calibrations allows the gain to be determined to an accuracy of better than ±0.2% at any time. The detector system was mounted equatorially on a platform, which was magnetometer stabilized in azimuth to typically 0°.1. Sources could be tracked with an accuracy of 0°.3, with the actual pointing direction known to better than 0°.1. The telescope was pointed toward Her X-1 eight times for 20 minutes each. The observation periods were interrupted by off-source background measurements of 10 minutes duration with a detector off-set of 7° in declination from the source. The average atmospheric depth was 3.28 g cm^{-2}.

III. DATA ANALYSIS AND RESULTS

The barycentric arrival time of each photon was calculated and the pulsation period of Her X-1 determined to be 1.2377963±0.0000007 s for 1977 September 3.99 UT, consistent with the value found by Pravdo *et al.* (1977). By folding the arrival time of each event modulo this period into 40 bins we derived the light curves, which are shown for different energy intervals in Figure 1. The light curves are characterized by a

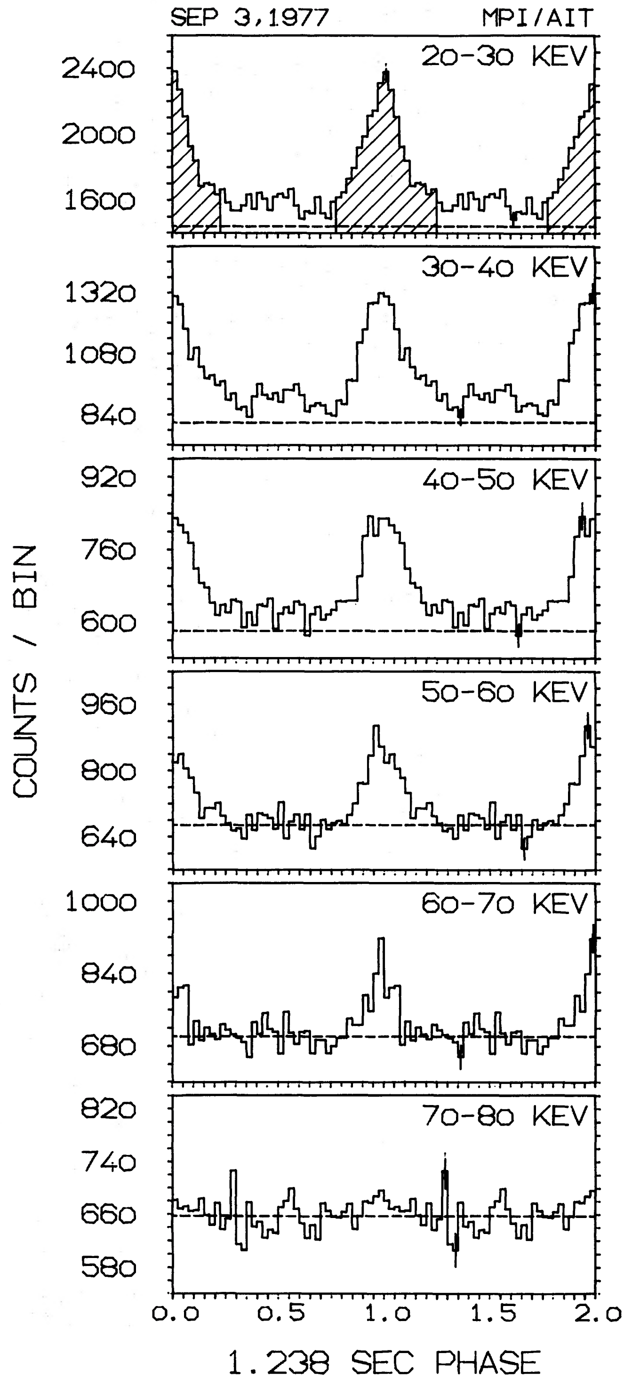

FIG. 1.—Her X-1 pulse profiles on 1977 Sep 3 for six different energy intervals. The horizontal dashed lines represent the off-source background level. Error bars shown are ±1 σ statistical deviations. The uppermost panel indicates the phase intervals defined as the pulse (*hatched*) and off-pulse region from which spectra were obtained.

narrow main pulse and a much smaller interpulse shifted by 180° in phase with respect to the main pulse. The 1.24 s pulsation is clearly visible up to an energy of 70

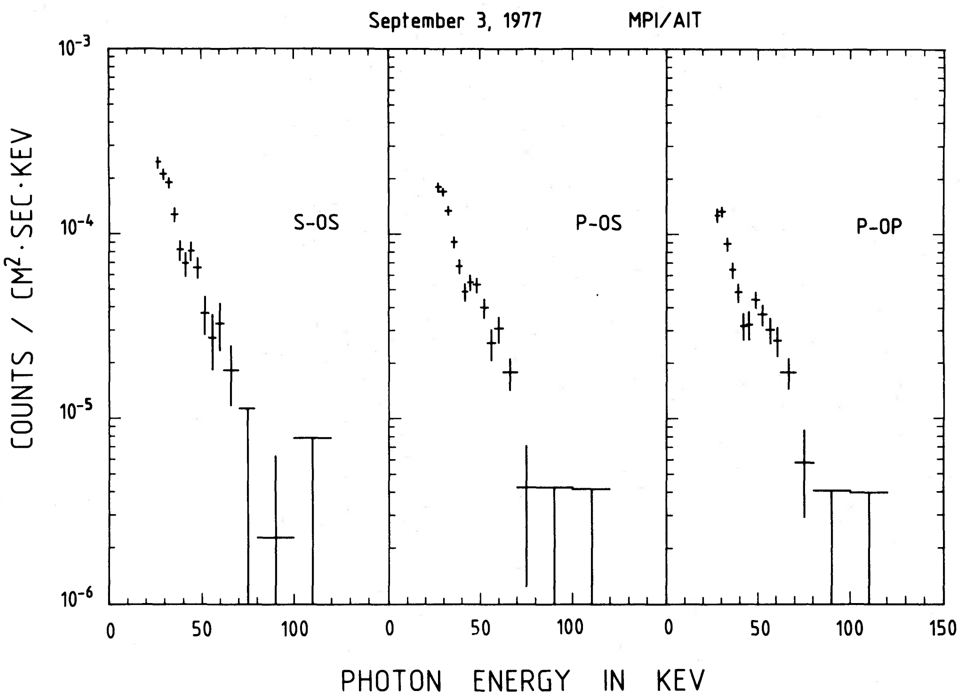

FIG. 2.—Her X-1 count rate spectra on 1977 Sep 3. (*a*) Source minus off-source spectrum, (*b*) pulse minus off-source spectrum, (*c*) pulse minus off-pulse spectrum. The error bars are $\pm 1\ \sigma$ statistical deviations; the upper limits are at $2\ \sigma$.

keV (a detailed description of the characteristics of the light curves will be discussed among other topics in a second paper by Voges *et al.* 1983).

In order to analyze the spectral properties of the source we consider the following spectra: (1) the total Her X-1 spectrum (source minus off-source = S—OS), (2) the spectrum corresponding to the main pulse of the 1.24 s pulsation (pulse minus off-source = P—OS), (3) the spectrum corresponding to the excess flux measured during the main pulse of the 1.24 s pulsation (pulse minus off-pulse = P—OP).

The last-named spectrum (P—OP) is the difference of two spectra and therefore has no direct physical meaning. However, it is free from all effects caused by spectral and temporal properties of the background and by gain shifts if any.

The Her X-1 pulse flux (P) was defined as the count rate in a 18 bin wide phase interval around the pulse maximum of the 1.24 s rotational period (hatched region as indicated in the upper light curve of Fig. 1), while the off-pulse flux (OP) was defined as the count rate in the remaining 22 phase bins.

The corresponding count rate S—OS, P—OS, and P—OP spectra are shown in Figures 2a–2c. It is obvious that these raw data spectra show a large deviation from any smooth continuum in the energy range between 35 and 60 keV. The effect is strongest in the P—OP and weakest in the S—OS spectrum. Taking into account the atmospheric absorption, detection efficiency, energy resolution, and K-iodine escape, we have deconvoluted the data using a variety of different source spectra:

(1) exponential

$$= I_0(30\ \text{keV}) \exp[-(E-30)/E_0](E/30)^{-1};$$

(2) two exponentials

$$= (1)\ \text{exponential} + I_1(30\ \text{keV}) \exp[-(E-30)/E_1] \times (E/30)^{-1};$$

(3) exponential + blackbody

$$= (1)\ \text{exponential} + I_{bb} E^2/[\exp(E/E_1) - 1];$$

(4) exponential + emission line

$$= (1)\ \text{exponential} + I_{\text{Line}} G(E, E_{\text{Line}}, \text{FWHM});$$

(5) exponential + absorption line

$$= (1)\ \text{exponential}\,[1 - EwG(E, E_{\text{Line}}, \text{FWHM})];$$

with $G(E, E_{\text{Line}}, \text{FWHM}) = 0.94 \exp\{-[(E - E_{\text{Line}})/\text{FWHM}]^2\}/\text{FWHM}$.

The energy E is given in keV. The exponential spectrum has been normalized at 30 keV, which is within our sensitive energy range, in order to minimize uncertainties in the determination of the intensity parameter. The exponential spectrum has been chosen for pragmatic reasons, in order to facilitate comparison with other measurements. We note that an optically thin bremsstrahlung spectrum which contains a somewhat different energy dependence (the factor is $E^{-1.4}$ rather than E^{-1}) would fit the data equally well, although the fit parameters would be a little different.

For the fits the energy range was divided into 15 channels between 26 keV and 120 keV. Available data points below 26 keV were not used because of the known spectral break energy around 23 keV (Becker *et al.* 1977; Gruber *et al.* 1980; Pravdo *et al.* 1978).

The resulting best-fit parameters including the $\chi^2_{\min}$ values and the significances α are summarized in Table 2. The errors quoted are for a joint 68% confidence region in parameter space. For the five-parameter fits this corresponds to $\chi^2_{\min}+5.9$. Using the significance $\alpha \geq 10\%$ as an acceptance criterion for a fit (Lampton, Margon, and Bowyer 1976), we find that a single continuum (exponential spectrum) as well as two continua (two exponential spectra, or exponential spectrum plus blackbody spectrum), fail to give acceptable fits to the P—OS and P—OP type spectra. The same holds true for single or double power law spectra, not shown in Table 2. Only the S—OS spectrum can be marginally represented by these model spectra. Clearly the spectral shape in the 35–60 keV region is too sharp to be modeled by the superposition of two continuum spectra. On the other hand, the inclusion of a Gaussian line profile to the exponential spectrum—either as an emission line or as an absorption line—results in well acceptable fits for all three types of Her X-1 spectra. There is no difference, as far as the statistical significance is concerned, between an emission line model and an absorption line model.

Comparing the spectral fits 4 and 5 in Table 2, we note that for the emission line model the *e*-folding energy E_0 is around 6.5 keV while the line is resolved and has a width of 21 (+8.6, −7.4) keV FWHM. In the absorption line model $E_0 \sim 13$ keV while the line width appears to be rather small. The deconvoluted P—OS and P—OP spectra of Her X-1 are shown in Figure 3: (*a*) for the emission line model, and (*b*) for the absorption line model. Comparing P—OS with P—OP spectra, we see that in the case of the absorption line model the deconvoluted spectra look very much alike, whereas in the case of the emission line the feature is more pronounced in the P—OP than in the P—OS spectrum. In both cases (P—OS and P—OP) the shapes of the spectra differ markedly for the emission and absorption line models. The physical reason for this lies in the different width of the lines, as mentioned before.

The line feature has a statistical significance of more than 10 σ over the continuum in the energy range 43–80 keV, both for the emission and for the absorption interpretation (Table 2). Figure 4 shows the residual Her X-1 intensity after subtracting (*a*) the best exponential continuum fitted up to 43 keV (first vertical panel), (*b*) the exponential part of the emission line model (second vertical panel), and (*c*) the exponential part of the absorption line model (third vertical panel), using S—OS, P—OS, and P—OP data. The shape of the line feature appears to be symmetric about 38 keV (mean value in the case of absorption) whereas the emission feature appears to be asymmetric. The rise at low energies is steep (of the order of ~10 keV), and the falloff at higher energies is more gradual (of the order of ~25 keV).

To investigate spectral variability as a function of pulse phase, spectra of type (4) were fitted to the source count rate spectra for individual phase intervals of the 1.24 s pulse period. In the first step we applied a five-parameter fit to the data. Since the line width showed no systematic variations with the pulse phase, this parameter was held fixed at a value of 21.4 keV FWHM in a second step. The corresponding phase-dependent P—OS spectra are shown in Figure 5 (with an insert to indicate the pulse phase region investigated). The spectra are normalized to the same phase length. As clearly visible the line feature is particularly pronounced in the two spectra around phase 0. In Figure 6 we show the dependence of spectral fit parameters on the pulse phase. Since the statistical significance of the spectral feature is very low in the off-pulse region, we have omitted the corresponding point in Figure 6*b*. For the same reason the points plotted at phase $\phi = 0.5$ must be considered with some caution; they are just the result of the formal fit. A qualitative inspection of Figure 6 shows that the *e*-folding energy E_0 and the fractional line intensity do not exhibit significant variations over the pulse period, while the emission line centroid seems to show such a variation. To obtain a quantitative measure we have fitted to all three parameter sets, 6*a*–6*c*, three types of phase dependences: (1) a constant, (2) a straight line, and (3) a sine wave with the Her X-1 period. It turns out that the *e*-folding energy and the intensity ratio of the line to the continuum are indeed well represented by constant values. The other functions gave equally acceptable results without any indication for a preference of one of the three functions used. On the other hand, the measured variations of the emission line centroid $E_{\rm Line}$ can be represented by the sinusoidal function, which is plotted in Figure 6*c*. In the off-pulse region the sine wave has been dashed to indicate the low statistical significance. While a constant value can be ruled out, the straight line fit gives a χ^2 value, which is clearly below the acceptance level using the acceptance criterion mentioned above.

For a comparison with *HEAO 1* A-4 data (Fig. 12 in Rothschild 1981) we have analyzed their emission line centroid variations of 1978 February in the same way as ours. As a result we found acceptable fits for a straight line as well as a sinusoidal function. In the case of the

TABLE 2

HERCULES X-1 SPECTRAL PARAMETERS

Count Rate Spectrum	Fitted Function	p[a]	$(N-P)$[b]	χ^2_{min}	α[c] (%)	I_0 (10^{-4} ph/cm^{2}s keV)	E_0 (keV)	I_1 or I_{bb} (10^{-4} ph/cm^{2}s keV)	E_1 (keV)	Line Parameters: I_{line} (10^{-3} ph/cm^{2}s)	E_w (keV)	E_{line} (keV)	FWHM (keV)	Line Excess (43–80 keV)
S–OS	Exponential	2	13	29.6	0.6	10.7 ± 0.6	11.3 ± 1.1	...	...	...	...	...	...	...
P–OS				76.0	<0.1	7.8 ± 0.6	12.6 ± 1.4	...	...	...	...	...	...	...
P–OP				86.4	<0.1	5.8 ± 0.6	15.1 ± 2.5	...	...	...	...	...	...	
S–OS	Exponential plus exponential	4	11	17.3	10	$2.6^{+3.6}_{-2.6}$	3.4 ± 2.2	7.0 ± 2.7	16.7 ± 4.9	...	...	...	...	...
P–OS				32.8	0.1	2.1 ± 2.1	3.3 ± 1.6	4.8 ± 1.4	20.1 ± 5.1	...	...	...	...	...
P–OP				45.1	<0.1	$1.4^{+2.0}_{-1.4}$	2.9 ± 1.9	3.3 ± 1.1	24.7 ± 8.6	...	...	...	...	...
S–OS	Exponential plus blackbody	4	11	16.1	12	4.8 ± 3.3	4.1 ± 1.8	$0.16^{+0.18}_{-0.16}$	8.8 ± 1.6	...	...	...	...	...
P–OS				27.3	0.2	3.6 ± 1.8	3.8 ± 1.2	0.074 ± 0.057	9.8 ± 1.4	...	...	...	...	...
P–OP				36.9	<0.1	2.3 ± 1.6	3.4 ± 1.4	0.037 ± 0.031	10.9 ± 1.8	...	...	...	...	...
S–OS	Exponential plus Gaussian emission line	5	10	13.4	20	10.1 ± 2.0	6.7 ± 2.3	...	...	3.1 ± 3.0	...	48.6 ± 9.7	21.8 ± 16.1	$9.4\,\sigma$
P–OS				14.6	15	7.6 ± 0.5	$6.4^{+1.3}_{-0.8}$	...	...	2.7 ± 0.6	...	51.2 ± 2.8	$21.4^{+8.6}_{-7.4}$	$15.3\,\sigma$
P–OP				13.0	>20	5.5 ± 0.6	$6.2^{+1.6}_{-1.0}$	...	...	2.3 ± 0.5	...	53.9 ± 2.7	$17.9^{+8.8}_{-7.4}$	$14.5\,\sigma$
S–OS	Exponential plus Gaussian absorption line	4	11	10.3	50	13.1 ± 1.0	12.2 ± 0.9	...	...	...	3.2 ± 0.6	36.8 ± 1.4	3.0	$9.8\,\sigma$[d]
P–OS				10.5	50	10.3 ± 0.6	13.5 ± 0.7	...	...	...	4.3 ± 0.5	37.6 ± 0.8	4.0	$17.9\,\sigma$[d]
P–OP				14.3	>20	8.3 ± 0.9	15.3 ± 1.2	...	...	...	6.0 ± 0.9	38.3 ± 0.9	5.6	$20.3\,\sigma$[d]
S–OS	Exponential plus Gaussian absorption-line	5	10	[e]	[e]	[e]	[e]	...	...	...	...	...	...	...
P–OS				[e]	[e]	[e]	[e]	...	...	...	...	...	...	...
P–OP				14.0	>15	7.7 ± 1.2	15.7 ± 1.3	...	...	...	8.7 ± 2.5	38.2 ± 0.9	$5.8^{+8.1}_{-5.8}$	...
S–OS	Exponential up to 43 keV	2	4	3.1	>50	11.1 ± 0.3	7.9 ± 0.6	...	...	...	...	...	...	$7.5\,\sigma$
P–OS				2.0	>70	8.3 ± 0.2	7.7 ± 0.3	...	...	...	...	...	...	$12.7\,\sigma$
P–OP				4.7	30	6.0 ± 0.2	7.3 ± 0.7	...	...	...	...	...	...	$13.1\,\sigma$

[a] Number of adjustable parameters.
[b] Degrees of freedom.
[c] Significance of fit.
[d] Line deficit (26–50 keV).
[e] Fits do not give meaningful results.

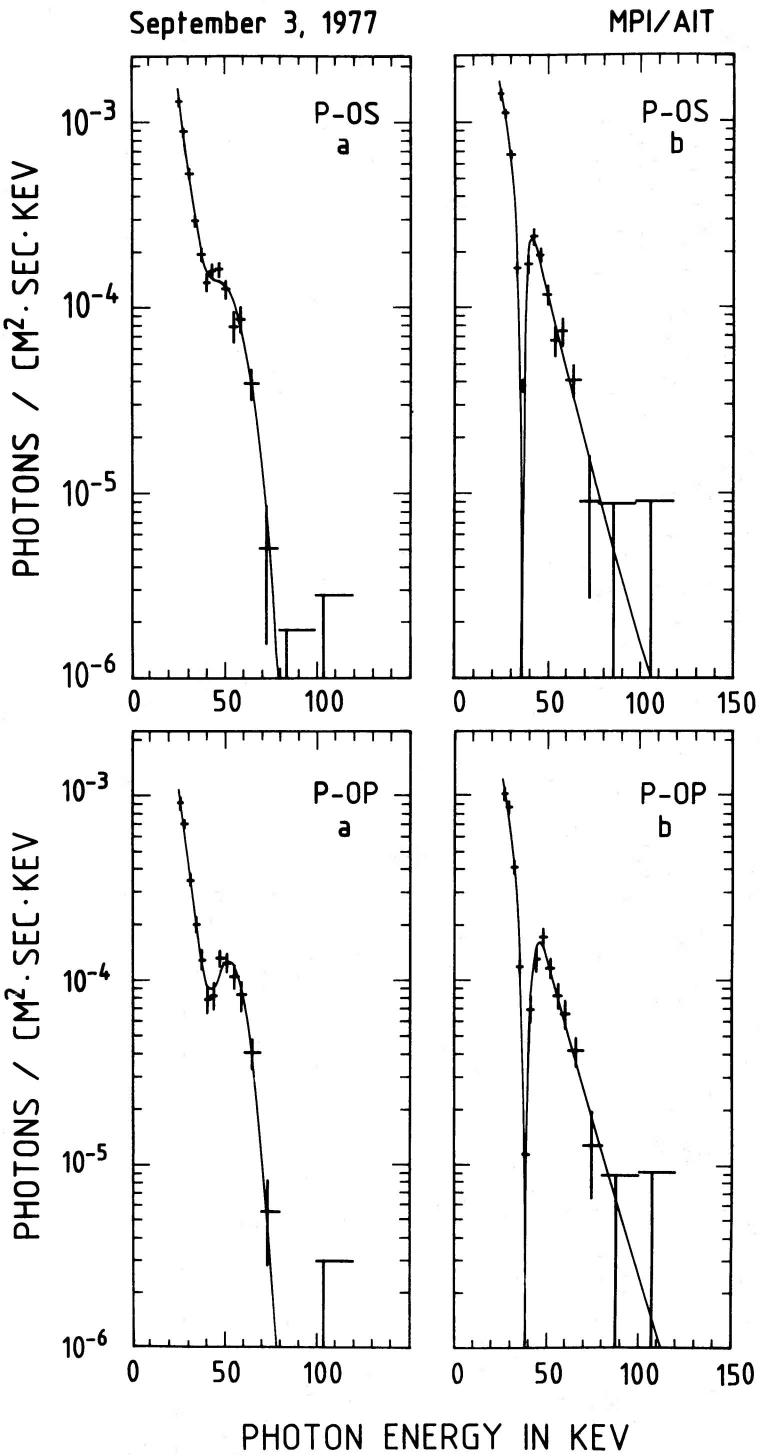

FIG. 3.—Deconvoluted photon spectra of Her X-1 pulse minus off-source (*upper panel*) and pulse minus off-pulse (*lower panel*) data on 1977 Sep 3. The solid lines represent the best-fitting exponential spectra with a Gaussian line (a) in emission or (b) in absorption to the data points. The error bars are $\pm 1\ \sigma$ statistical deviations, the upper limits are at $2\ \sigma$.

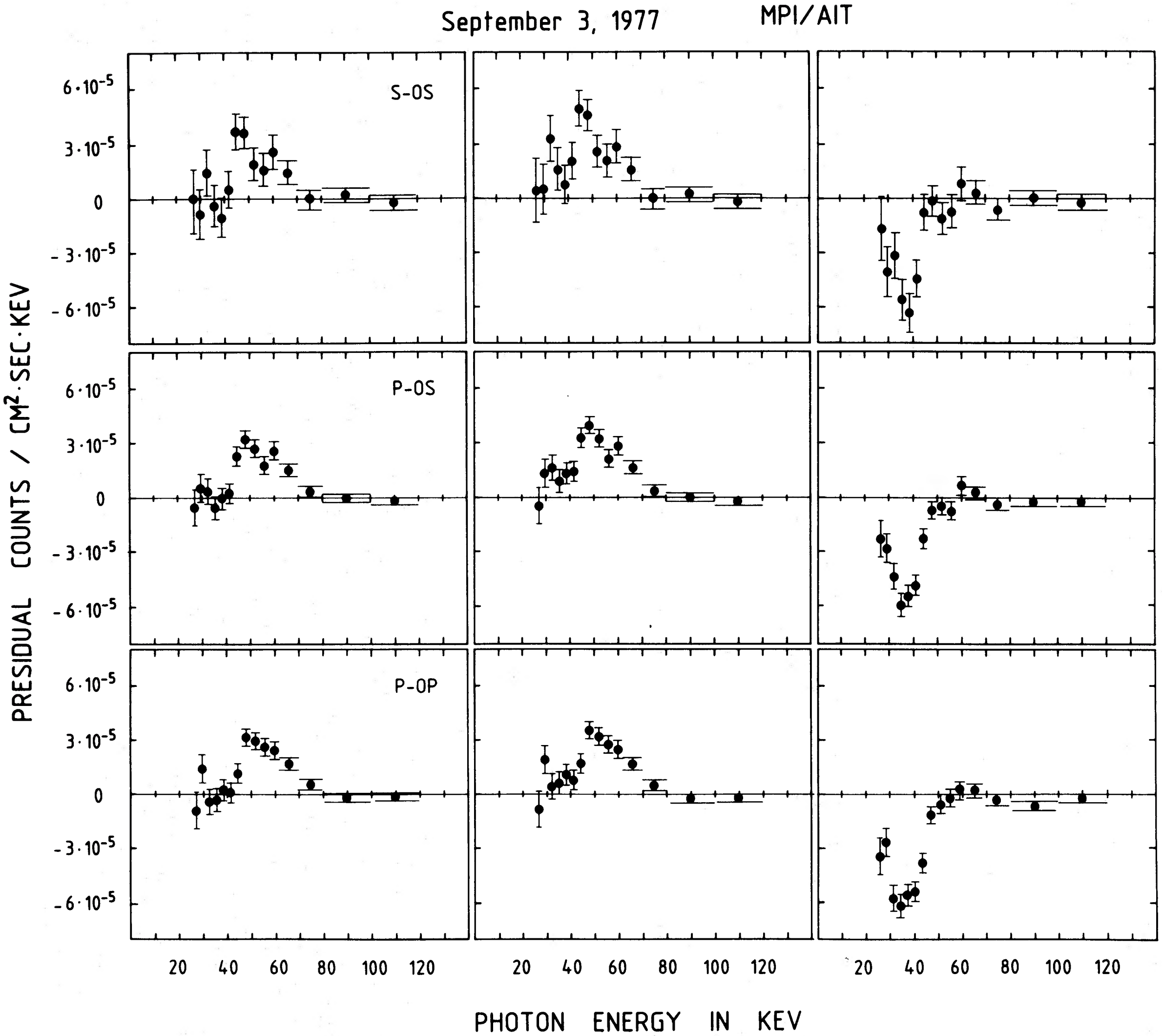

FIG. 4.—Residual Her X-1 intensity after subtracting (*a*) the best exponential continuum fitted up to 43 keV (shown in the first vertical panel), (*b*) the exponential part of the emission line model (second vertical panel), (*c*) the exponential part of the absorption line model (third vertical panel). The top, middle, and bottom panels represent results from the S—OS, P—OS, and P—OP spectra, respectively.

sinusoidal function, both sets of the three-parameter fits agree very well within the error limits. Figure 7 shows the combined data of *HEAO 1* and our balloon detector. Also plotted is the best sinusoidal function to all data points, which has the following form:

$$E_{\rm Line}({\rm keV}) = 39(\pm 4) + 14.5(\pm 3.5)*\sin[2\pi\phi + 2(\pm 0.2)].$$

The emission line centroid has its maximum at phase $\phi = -0.07$, i.e., $25° \pm 12°$ before the zero phase which we defined at the position where the light curve reaches its maximum in the 20–70 keV range. (We should mention that the fit parameters do not change significantly if we omit the off-pulse data point.)

Gruber *et al.* (1980) found some variation of the *e*-folding energy E_0 and the line centroid in the case of the absorption line model. Unfortunately, we cannot make a good direct comparison with these data because in our case the errors of the absorption model parameters are too large. This is largely due to the fact that our fits start only at 26 keV and corrections for atmospheric absorption are rather high at low energies. But if we compare their sinusoidal variation of the absorption line centroid determined for the entire pulse phase in 1978 August with the results of the combined *HEAO 1* and balloon data on the emission line centroid, we find that the amplitude in the case of the emission line centroid variation is about a factor 5–6 larger than for the absorption line. Second, the sinusoidal variations of the absorption line centroid may be shifted in phase with respect to the emission line modulation discussed above.

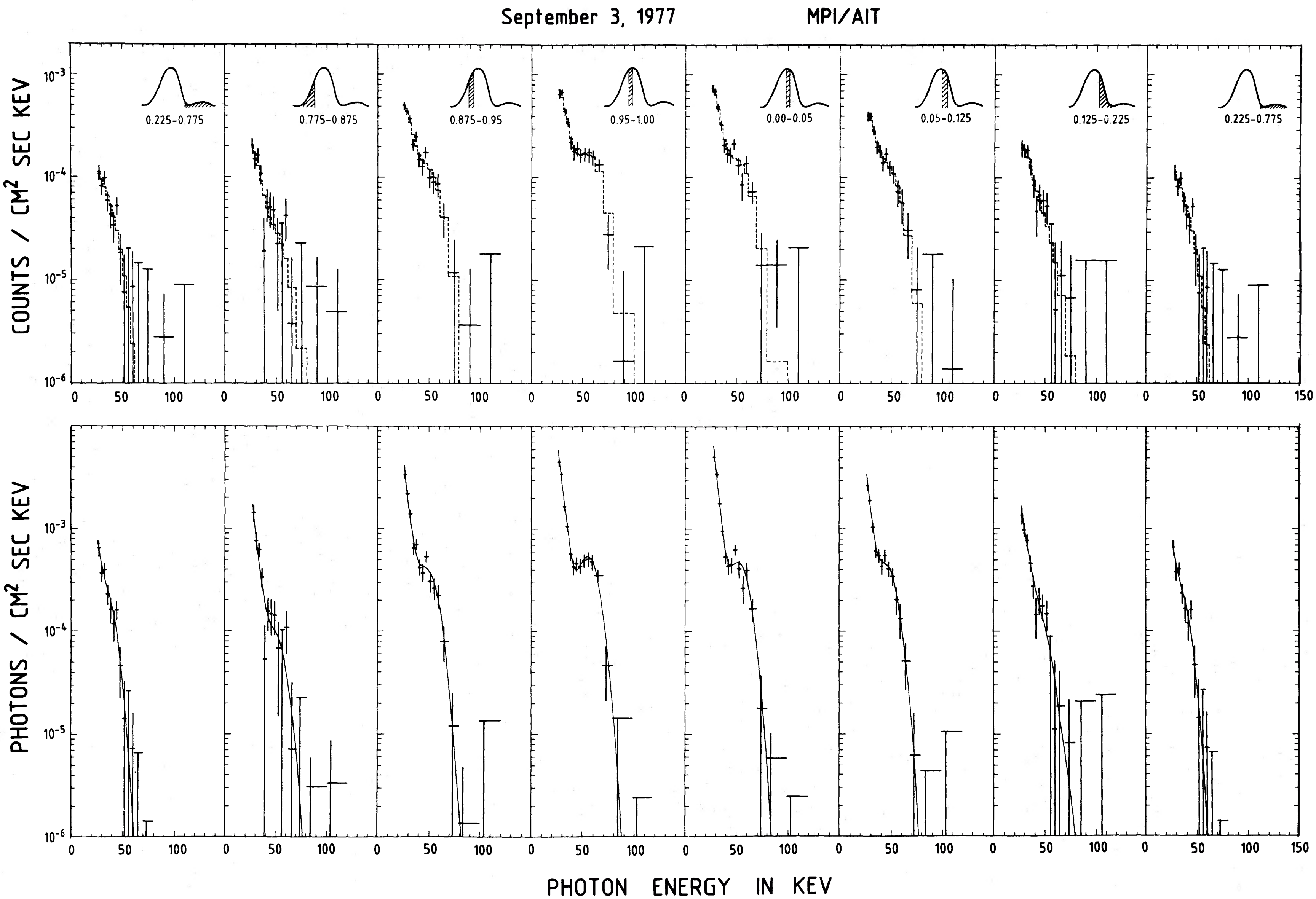

FIG. 5.—Phase-dependent pulse minus off-source spectra of Her X-1 on 1977 Sep 3. Upper panels represent count rate spectra, lower panels show deconvoluted photon spectra. Dashed and solid lines represent the best fit of an exponential continuum with an emission line to the data. The Gaussian line width was held fixed at 21.4 keV FWHM. Error bars are $\pm 1\ \sigma$, upper limits are at $2\ \sigma$. Also indicated in each subpanel as insert is the phase interval analyzed. (The spectra are normalized).

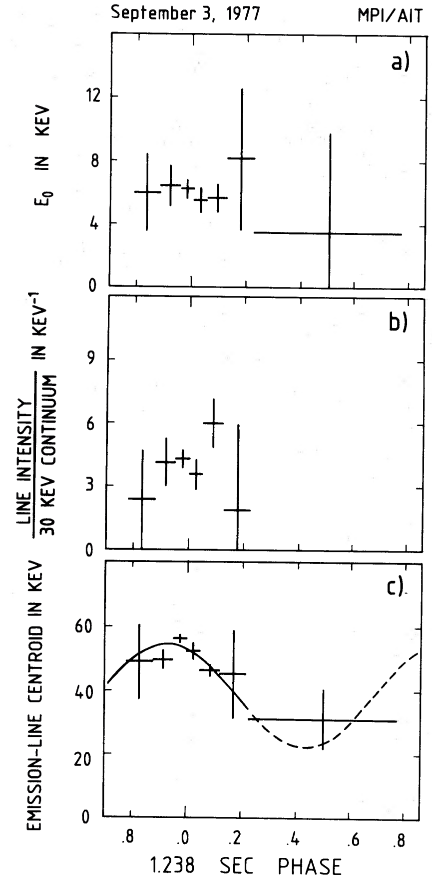

FIG. 6.—Best fit parameters of the pulse minus off-source spectra as a function of 1.238 s pulse phase using the emission line model. (a) Exponential e-folding energy E_0, (b) ratio of line intensity to continuum intensity at 30 keV, (c) emission line centroid (the solid curve indicates the best sinusoidal fit). Error bars are 1 σ deviation.

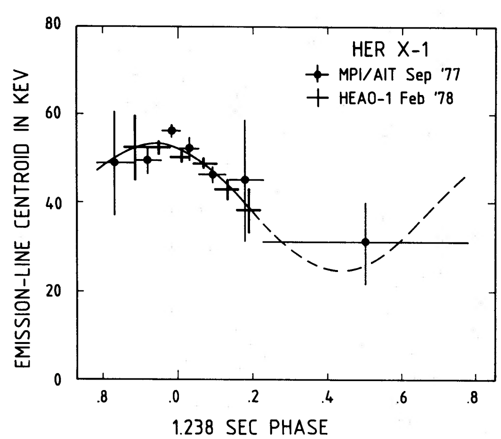

FIG. 7.—Combined *HEAO 1* A-4 (taken from Rothschild 1981) and MPI/AIT balloon-detector data on the emission line centroid variation with pulse phase. Indicated is the best sinusoidal function to all data points.

However, we are unable to judge upon the statistical significance of such a shift.

Searching for spectral variability during the observation time of 4.4 hours, we investigated individual P—OS spectra of the eight Her X-1 pointing intervals. Fitting a single continuum spectrum to the data in the energy range 26–43 keV revealed no statistically significant changes of the exponential e-folding energy E_0 with time. However, the continuum flux at 30 keV varied significantly by +20% and −15% from the mean value on a time scale of 20 minutes. The spectral feature in the energy range between 35 and 60 keV again is clearly visible in each individual Her X-1 pointing. A fit with a continuum plus emission line model revealed no significant variability of any one of the parameters E_0, $I_{\rm Line}$, $E_{\rm Line}$, and ratio I(line)/I(continuum).

Our 1976 May data (Trümper *et al.* 1977, 1978) had indicated a possible second line feature at ~110 keV with a statistical significance of 3.3 σ. A search at this energy in the 1977 September data had a null result. The corresponding 2 σ upper limit for the line flux at the expected line energy of ~100 keV is 2.4×10^{-4} photons cm^{-2} s^{-1} for the P—OS and P—OP spectra. The line intensity ratio is $I(100 \text{ keV})/I(52 \text{ keV}) \leq 0.1$ as compared with ~1 in 1976 May.

The intensity of the continuum in 1977 is the same as in 1976 within 10%. Also the line intensities measured in 1976 and in 1977 are consistent with each other within the error limits. In a paper based on a preliminary analysis of the same as the present data (Voges *et al.* 1979) a factor of about 2 intensity difference was claimed between the 1976 and 1977 data. However, these intensity values were normalized at an energy of 1 keV, far below the energy range of our measurements. Although formally correct, such intensity figures include large errors because they are strongly coupled with the e-folding energy. Since this was not properly taken into account, our statement about the intensity decrease was wrong.

IV. DISCUSSION

Our 1976 May observation (Trümper *et al.* 1977, 1978) and the preliminary data analysis of the present 1977 September data (Voges *et al.* 1979) had shown that the spectrum of Her X-1 reveals a strong and significant deviation from a smooth continuum which is best modeled by an emission or absorption line. The present final results of September 1977 confirm this deviation with a large significance. The spectral structure which has to be added to a smooth continuum is too sharp to be modeled by a second continuum spectrum (cf. Figs. 2a–2c). On the other hand, the addition of a line gives an excellent fit.

Independent confirmation for the existence of this spectral feature in the Her X-1 ON state spectrum has been reported by Gruber *et al.* (1980) and Scheepmaker

TABLE 3

BEST SET OF CYCLOTRON LINE PARAMETERS DERIVED FROM *HEAO 1* AND MPI/AIT OBSERVATIONS

Parameter	Emission Line	Absorption Line
Energy (keV)	52	38
Intensity	3.0×10^{-3} photons cm^{-2} s^{-1}	5.0 keV equivalent width
Width (FWHM) of Gaussian profile ...	21 keV	9 keV

et al. (1981) while several other less sensitive observations have found results which are largely consistent with our picture (Evans, Quenby, and Engel 1980; Maurer et al. 1979; Pravdo, Bussard, and White 1979; Pravdo *et al.* 1979; Tueller *et al.* 1981; Ubertini *et al.* 1981; for a compilation of data see Staubert *et al.* 1981).

Our 1977 and the *HEAO 1* 1978 measurements agree well within statistical uncertainties regarding the line energy, intensity, and width. Table 3 gives what appears to be the best parameter set derived from these observations.

As far as the intrinsic line width is concerned, the errors are quite large due to the limited detector resolution ($\sim20\%$) of these scintillation counter measurements. As seen from Table 2, the present P—OS spectrum has a width of 21.4 ($+8.6, -7.4$) keV for an emission line. The corresponding 1976 data yielded 11.2 ($+26.4, -11.2$) keV, which is consistent with the new data. The same holds true for the *HEAO 1* measurements which give 28 ± 7 keV for the P—OP spectrum. Despite these uncertainties it appears that the line is resolved and has an intrinsic width of ~21 keV. Similar considerations can be made in the case of an absorption line, where we find for the P—OP spectrum 5.8 ($+8.1, -5.8$) keV while the *HEAO* 1 data yield 11 ± 4 keV. A weighted mean is ~9 keV. Although these errors are quite large, it appears that the line is considerably narrower than in the case of the emission line model.

On the other hand, the germanium spectrometer measurements of Tueller *et al.* (1981) have good spectral resolution ($\sim2\%$) but a much lower signal-to-noise ratio. The line energies quoted by these authors appear to be somewhat smaller, but at the same time the *e*-folding energy of the continuum component is smaller by approximately the same factor. It is not clear whether this discrepancy is due to a systematic difference in the detector response or to a source variability. Concerning the line width, the germanium spectrometer data support the view that the line is not very narrow. The quoted value of ~13.5 keV, for both the emission line and the absorption line, is consistent with the above data within the error limits.

As already discussed in our early papers (Trümper *et al.* 1977, 1978; Voges *et al.* 1979), it is difficult to explain the observed features by atomic or nuclear lines, because the necessary heavy elements have abundances too small to produce the observed line strength. In principle it seems possible that the resonances are due to atomic lines of more abundant elements like iron in superstrong magnetic fields. However, in order to shift the Fe^{25+} Lyα and Lyβ lines to ~50 keV, one needs magnetic field strengths of $\sim10^{14}$ gauss (Burdyuzha and Pavlov-Verevkin 1981; Ruder *et al.* 1981), a value which seems to be unlikely. In addition, it is difficult to believe that the abundances of Fe^{25+} or any other likely element are large enough to produce the observed effects. Therefore we reject these possibilities and conclude that the most plausible interpretation is in terms of the first harmonic electron cyclotron resonance in a superstrong magnetic field. From the shape of the continuum spectrum it is evident that the temperature in the polar hot spot of Her X-1 is of the order of 10–30 keV, which means that almost all matter is completely ionized. Electrons are the most abundant species, and because of the large cross sections the electron cyclotron resonance should appear in emission or absorption, depending on the Thomson optical thickness of the radiating plasma (cf. Nagel 1981) and on the temperature distribution (Trümper 1979). A large number of attempts have been made during the last few years to build models of Her X-1, but no self-consistent picture has emerged so far (for references see Trümper 1982; Kirk and Trümper 1982).

From these models it appears most likely that the observed spectral features are seen in absorption (or scattering) rather than in emission; however, the latter case cannot be excluded (Trümper 1982). At any rate, the polar magnetic field of Her X-1 should be approximately 4×10^{12} gauss (3.4×10^{12} gauss for absorption, 4.7×10^{12} gauss for an emission line), neglecting the gravitational redshift of the emitted radiation which gives rise to an upward correction of 10%–20%.

We note that the "second harmonic" cyclotron resonance which seemed to be present in our 1976 data has not been seen again. One possibility is that the 3.3 σ detection in 1976 was just a statistical fluctuation. Another possibility is that the temperature in the Her X-1 polar hot spot was somewhat higher during the 1976 observation, compared with later sightings. Since the second harmonic feature is located in the extreme

"Wien" part of the spectrum, it may be strongly temperature dependent.

Of particular interest is the observed variation of the line feature energy with the phase of the 1.24 s pulsation which confirms and improves on the *HEAO 1* findings (Gruber *et al.* 1980; Rothschild 1981). Such variations of spectral shape in the cyclotron resonance region are not unexpected because the emission characteristics of the hot polar plasma will depend on the polar angle ϑ, measured with respect to the magnetic field direction. For instance, the effects may be due to thermal Doppler broadening (Trümper 1978; Bussard 1980) or to Doppler line shifts if absorbing/scattering material is not at rest but in semirelativistic motion. In addition, there may be a variation of the effective cyclotron frequency if the emission or absorption region has such a large vertical extent that the radial decrease of the magnetic field is not negligible. A more detailed discussion of these effects will be given elsewhere.

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