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NASA
Technical Memorandum 79591

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(NASA-TM-79591) DISCCVERY CF IRON IINE EMISSION IN THE HERCULES X-1 LOW STATE SPECTRUM WITH HEAC-1 (NASA) 17 p HC A02/MF A01 CSCL 03E

N78-31038

Unclas
G3/93 29343

JULY 1978

National Aeronautics and
Space Administration

Goddard Space Flight Center
Greenbelt, Maryland 20771

Discovery of Iron Line Emission in the Hercules X-1 Low State Spectrum with HEAO-1

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ABSTRACT

We report the discovery of an iron line emission feature in the low state spectrum of Hercules X-1. Four characteristics of this line distinguish it from Hercules X-1 high state line emission: the line energy, equivalent width, binary phase dependence, and intrinsic width. We use these findings to discuss secondary X-ray emission from this binary system.

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I. INTRODUCTION

The low state in the 35-day high-low cycle of Hercules X-1 (Giacconi et al. 1973) provides an excellent opportunity to observe the secondary X-ray emission in the Hercules X-1 - HZ Herculis binary system. The secondary emission could arise from the reflection of Her X-1 X-rays by the atmosphere of HZ Her (Basko, Sunyaev, and Titarchuk (BST) 1974), the photo-ionization and subsequent fluorescence emission from atomic iron in the system (Felsteiner and Opher 1976), or a combination of these from other ambient material (Jones and Forman 1976, Basko 1978). The HEAO-1 satellite observatory performed a series of pointed observations at Her X-1 between February 24 - March 7, 1978. During the first two points Her X-1 was in its high state. We confirm the existence of the iron line emission feature discovered with OSO-8 (Pravdo et al. 1977 hereafter Paper I) in the high state spectrum. During the last two points, observations of the Her X-1 low state reveal an iron emission feature which is normally a minor component of the high state line emission. We discuss this new line feature and the X-ray spectrum during the low state.

II. EXPERIMENT AND ANALYSIS

The HEAO-1 A2 experiment+ consists of six gas proportional counters covering the energy range between 0.1 and 80 keV (see Rothschild et al. 1978 for further details). This work will discuss the results of data obtained from two of the three high energy detectors (HED) and one medium energy (MED) detector. Table 1 reviews the characteristics

+ The A2 experiment on HEAO-1 is a collaborative effort led by E. Boldt of GSFC and G. Garmire of CIT, with collaborators at GSFC, CIT, JPL and UCB.

of the HED and MED modules pointed along the positive Y axis.

The method of spectral analysis is discussed By Serlemitsos et al. (1975) and Pravdo et al. (1978a). The experiment also has 80 msec temporal resolution in one normal telemetry mode. We therefore were able to observe the 1.24 sec pulse in the high state points and search for pulsations in the low state points.

III. RESULTS

Hercules X-1 made a transition from a low state to a high state near February 21, 1978 based upon our quick look data obtained during low-duty-cycle scans of the source. The X-ray intensity and spectrum observed at the first two points agree well with previous measurements during the high state (Clark et al. 1972, Holt et al. 1974). Spectral parameters are listed in Table 2. The distance to Her X-1 used to calculate the luminosity is 5.8 kpc (Forman, Jones, and Liller 1972). We confirm the existence of a highly significant (> 20σ) broad emission feature near 6.8 keV with an equivalent width of $\sim$ 300 eV or 6.5 $\pm$ 0.5 x 10^{-3} photons cm^{-2} sec^{-1} in the pulse-phase-averaged spectrum. The continuum is flat (power law index $\sim$ 0.9) and cuts off sharply near 20 keV. This spectrum is discussed in more detail elsewhere (Pravdo et al. 1978b). The total emission is pulsed with a heliocentric period of 1.237794 $\pm$ 0.000001 (1σ) sec (obtained from preliminary data). The double-peaked pulse has all the characteristics of previously observed Her X-1 pulses (Doxsey et al. 1973, Holt et al. 1974, Joss and Fechner 1975).

By March 6, 1978 the high state was over. The X-ray intensity decreased by a factor of $\sim$40 from the high state level. Our scanning data indicates that there are no low luminosity sources (> 10^{-11} erg cm^{-2} sec^{-1}) within 3^{0} of Her X-1 which could seriously contaminate this observation. We have detected the presence of an iron line emission feature--> 5σ significance each in two detectors and > 4σ in the third-- in the low state spectrum which has the following characteristics.

1) The line energy is 6.4 keV.

2) The equivalent width of the line exceeds that of the high state line.

3) The line intensity exhibits binary phase dependence.

4) The line is intrinsically narrow in contrast to the broad high state line.

Figure 1 illustrates the binary-phase-averaged low state spectrum obtained with two of the three detectors. The PHA count distributions clearly show a 6.4 keV emission feature.

The low state line energy is 6.4 $\pm$ 0.1 (1σ) and our best fit indicates that the line is narrow with an intrinsic width upper limit of 550 eV. This is in contrast to the line parameters determined only days earlier by the same detector in the high state spectrum. In that case a broad line with intrinsic full width at half maximum of 1.3 $\pm$ 0.2 keV and a central energy of 6.8 $\pm$ 0.1 keV best fit the data. We find that the high state line can also be described as double lines separated by $\sim$1 keV in line energies (see also Paper I).

The line equivalent width in the low state averaged over observed binary phase is 0.65 (+0.03, -0.14) keV which corresponds to 4.4 (+0.2, -0.9) x 10^{-4} photons cm^{-2} sec^{-1}. This is approximately twice the equivalent width measured in the high state. Near binary phase 0.5 the equivalent width increases to 0.88 $\pm$ 0.25 keV and the line photons to (5.3 $\pm$ 1.) x 10^{-4} photons cm^{-2} sec^{-1}. The increase in line photons near midphase over those in the earliest observed phase is of low statistical significance ($\sim 2\sigma$), but it occurs in all three detectors, and may be real.

We have analyzed the low state continuum spectra at early and middle binary phase (Fig. 2). The 1σ joint confidence contours for the number index and the column density of cool material (Brown and Gould 1970, Fireman 1974) in the line of sight are inset in the Figure for each spectrum. The continua are similar to the high state continuum (see also Jones and Forman 1976) although there is a $< 1\sigma$ indication in three detectors that the low state continuum is flatter. There is no evidence for continuum changes with binary phase. We note that the HED 3 spectrum indicates that the high energy cutoff near 20 keV is present (Becker et al. 1977) with 5σ significance. A search for pulsations at the previously determined pulse period discovered none with a 1σ pulsed fraction upper limit of 0.005 (see also the two references above).

IV. DISCUSSION

The properties of the emission line feature discovered with HEAO-1 in the Hercules X-1 low state spectrum suggest strongly that we have isolated a component of the iron line emission from this system. If it were present during the high state at the same intensity, this emission would contribute an average of only $\sim$ 15 eV to the equivalent width. It is clearly dominated in this case by the $\sim$ 300 eV of line emission from material in the Alfven shell (Paper I, Ross, Weaver, and McCray 1978). During the low state both the neutron star and the Alfven shell are shielded from our field of view. One clear indication of this is that the soft X-rays which presumably originate in the shell (McCray and Lamb 1976, Basko and Sunyaev 1976) also decline in the low state (McClintock et al. 1974, Shulman et al. 1975, Kahn 1978).

We know, however, from optical observations of HZ Her that although we can not see most of them, X-rays are still generated in the system during the low state: HZ Her continues to undergo a 1.7 day X-ray heating cycle (Bahcall and Bahcall 1972; Forman, Jones, and Liller 1972; BST). Therefore fluorescence emission from the system is expected. The observed line energy of 6.4 keV and the narrow line width are consistent with this interpretation. It is unlikely that this line is the reflected high state line. First, its equivalent width is too high, and second, Compton scattering would tend to broaden line features (cf. Ross, Weaver, and McCray 1978; Pozdnyakov, Sobol, and Sunyaev 1978).

We can make the following deductions concerning the location of the fluorescing region and its temperature, based on the binary phase and spectral results presented above. First, we conclude that the surface of HZ Her is, at most, a minor source of the observed line and continuum X-rays. BST and Hatchett and Weaver (1977) have shown that the eclipse of X-rays reflected from HZ Her lasts about twice as long as the direct X-ray eclipse, so that there should be no line photons from this source at binary phases < 0.2. For this reason we must identify the early phase line emission with other iron in the system. In addition, BST and Felsteiner and Opher (1976) calculated that the spectrum of continuum X-rays reflected from HZ Her would be deficient at low energies, peak near 10 keV, and exhibit a marked binary phase dependence with a peak in intensity at phase 0.5. Clearly the low state continuum emission is dominated by a component which does not have these properties (see Table 2). Since the magnitude of the entire observed flux (3% of the high state) falls short of the albedo estimates of the above authors for the reflected flux from HZ Her alone, we conclude that HZ Her contributes $\lesssim$ 1/10 of the predicted flux. In this case, it may be fortuitous that the residual line emission near phase 0.5 (i.e. after the early phase emission is subtracted) is in good agreement with the prediction of Basko (1978) for fluorescence from HZ Her.

The absence of pulsations and of low energy absorption in the low state continuum flux indicates that this emission is reflected from a highly ionized plasma (Jones and Forman 1976, Becker et al. 1977). We can constrain the equilibrium temperature of this region to be $\lesssim 10^7$ K from the 6.5 keV upper limit to the fluorescent line energy (cf. House 1969, Jordan 1970, Raymond 1978), and to be $\gtrsim 10^7$ K from the absence of significant low energy absorption or absorption edges. A temperature of $\sim 10^7$ K could arise in a hot coronal gas out-flowing from HZ Her (Basko and Sunyaev 1973, Milgrom and Salpeter 1975). Basko (1978) estimates that this region can contribute more line photons than the HZ Her surface, and that this emission would be present at the earliest phase observed here.

The early phase line emission and the continuum spectrum indicate that a hot coronal gas is an important source of low state X-rays. The possibility that some of the line emission is reflected from the HZ Her surface must be questioned because of the failure to detect the continuum component. Theoretically, we must improve understanding of the X-ray albedo of HZ Her and perhaps of the 1.7 day HZ Her heating cycle. Future observations closer to an X-ray eclipse in the low state (Basko 1978) can reveal more about the constituents of this system.

We gratefully acknowledge the efforts of the many talented and dedicated individuals at GSFC who have contributed to the design, testing, and software development for the experiment. We also thank Drs. F. Marshall, J. Swank, and B. Smith for useful discussions. We acknowledge the helpful comment of the anonymous referee.

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TABLE 1

HEAO-1 A2 GSFC +Y AXIS DETECTORS

	DETECTION GAS	ENERGY RANGE (keV)	AREA (cm^2)	FIELDS OF VIEW (RECTANGULAR)	CALIBRATION SOURCE	VETO LAYER	PHA CHANNELS
MED	Argon	1.5 - 20	820	$3^o \times 3^o$ $3^o \times 1.5^o$	Fe^{55}	---	64
HED 3	Xenon	2 - 80	820	$3^o \times 3^o$ $3^o \times 1.5^o$	Am^{241}	Propane	64
HED 2	Xenon	2 - 80	844	$3^o \times 3^o$ $3^o \times 6^o$	Am^{241}	---	32

TABLE 2

HEAO-1 A2 SPECTRAL PARAMETERS FOR HERCULES X-1 POINTS

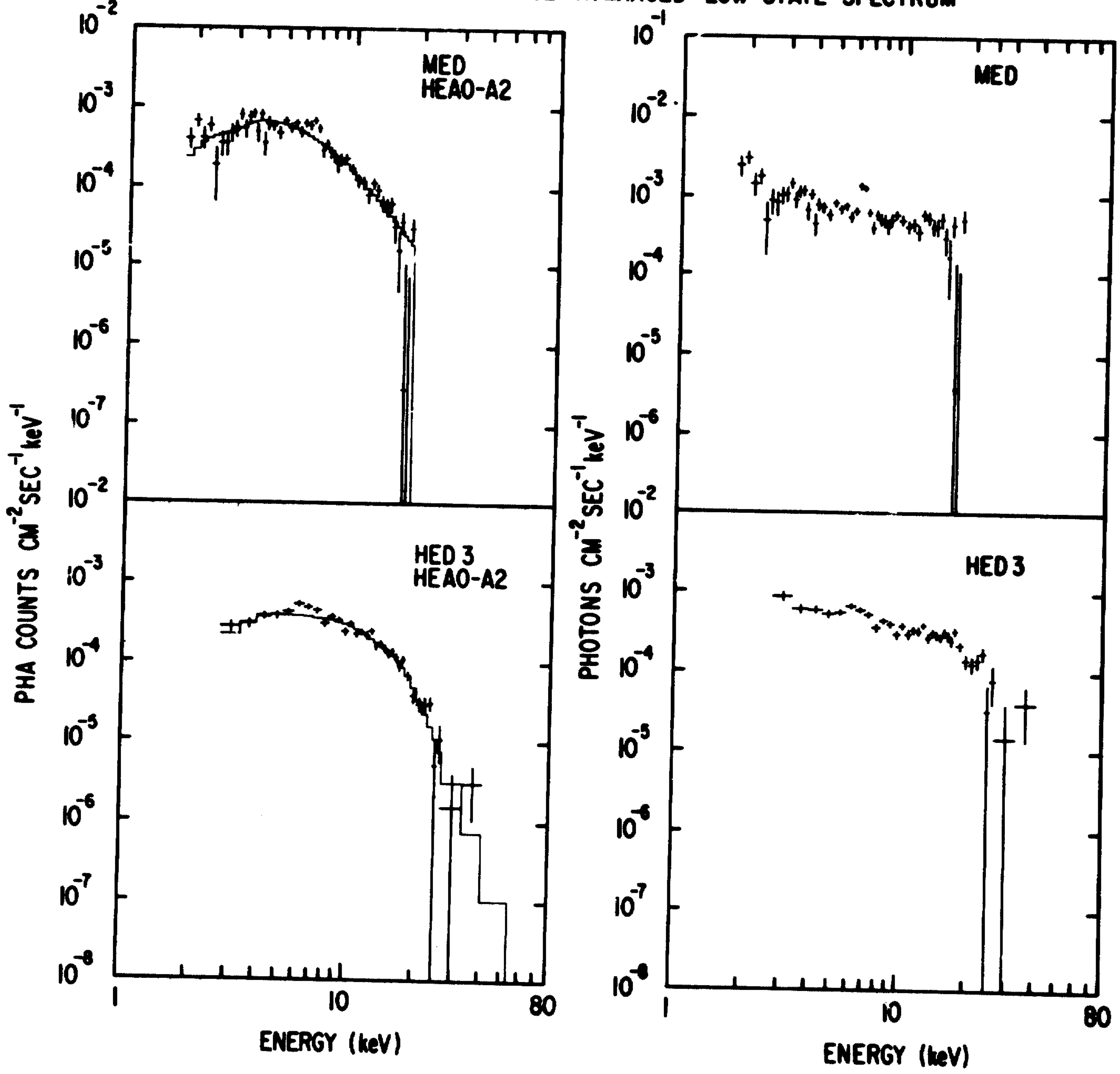
HERCULES STATE	UT (DAY OF 1978)	BINARY PHASE	L_x (2-20 keV) x 10^{-37} ergs^{-1}	NORMALIZATION	α POWER LAW INDEX	N_H H ATOMS cm^{-2} x 10^{-21}	LINE EQUIVALENT WIDTH (keV)	LINE PHOTONS cm^{-2} sec^{-1} keV^{-1} x 10^4	χ^2/DEGREES OF FREEDOM	DETECTOR
HIGH	55.62 -55.76	.309 - .347	1.9 ± .01	.155 ± .002	.95 ± .01	1.5 ± 0.2	.28 ± .03	73. ± 8.	109/45	MED
					DETECTOR	MODE	CHANGE			HED 3
			2.0 ± .01	.140 ± .001	.87 ± .01	0 + 1.8	.28 ± .03	78. ± 8.	107/22	HED 2
HIGH	58.66 -58.74	.096 - .141	1.7 ± .01	.128 ± .002	.89 ± .01	0 + 1.0	.33 ± .02	70. ± 6.	66/45	MED
					DETECTOR	MODE	CHANGE			HED 3
			1.9 ± .01	.150 ± .001	.93 [illegible]	7.2 ± 3.6	.20 ± .07	49. ± 17.	66/22	HED 2
LOW	65.56 -65.62	.153 - .191	0.056 ± .001	(2.57 ± .4) x 10^{-3}	.80 ± .15	0 + 5.	.34 ± .20	2.8 ± [illegible].2	49/45	MED
			0.040 ± .002	(2.19 ± .5) x 10^{-3}	.63 ± .15	0 + 27.	.42 ± .20	2.2 ± 1.5	44/43	HED 3
			0.040 ± .001	(7.58 ± 1.5) x 10^{-3}	.88 ± .1	0 + 18.	.20 ± .20	2.5 ± 2.5	14/10	HED 2
LOW	65.63 -65.69	.192 - .231	0.057 ± .002	(1.6 ± 0.4) x 10^{-3}	.55 ± .1	1.8 ± 1.8	.91(+2.,-0.42)	5.8(+10, -3.)	46/45	MED
			0.041 ± .002	(1.35 ± .2) x 10^{-3}	.58 ± .1	0 + 1.8	.75 ± .25	3.3 + 1.4	48/43	HED 3
			0.051 ± .002	(2.67 ± .4) x 10^{-3}	.76 ± .1	0 + 3.6	.25 ± .15	1.5 ± 0.7	30/10	HED 2
LOW	66.03 -66.09	.432 - .469	0.051 ± .002	(3.02 ± .5) x 10^{-3}	.84 ± .20	16. ± 16.	.88 ± .25	5.3 ± 1.0	51/45	MED
			0.048 ± .001	(1.24 ± .6) x 10^{-3}	.46 ± .1	0 + 10.	.55 ± .25	3.0 ± 1.2	51/43	HED 3
			0.048 ± .003	(5.5 ± 1.7) x 10^{-3}	1.1 ± .15	18. ± 18.	.61 ± .11	4.5 ± 1.5	3/10	HED 2

FIGURE CAPTIONS

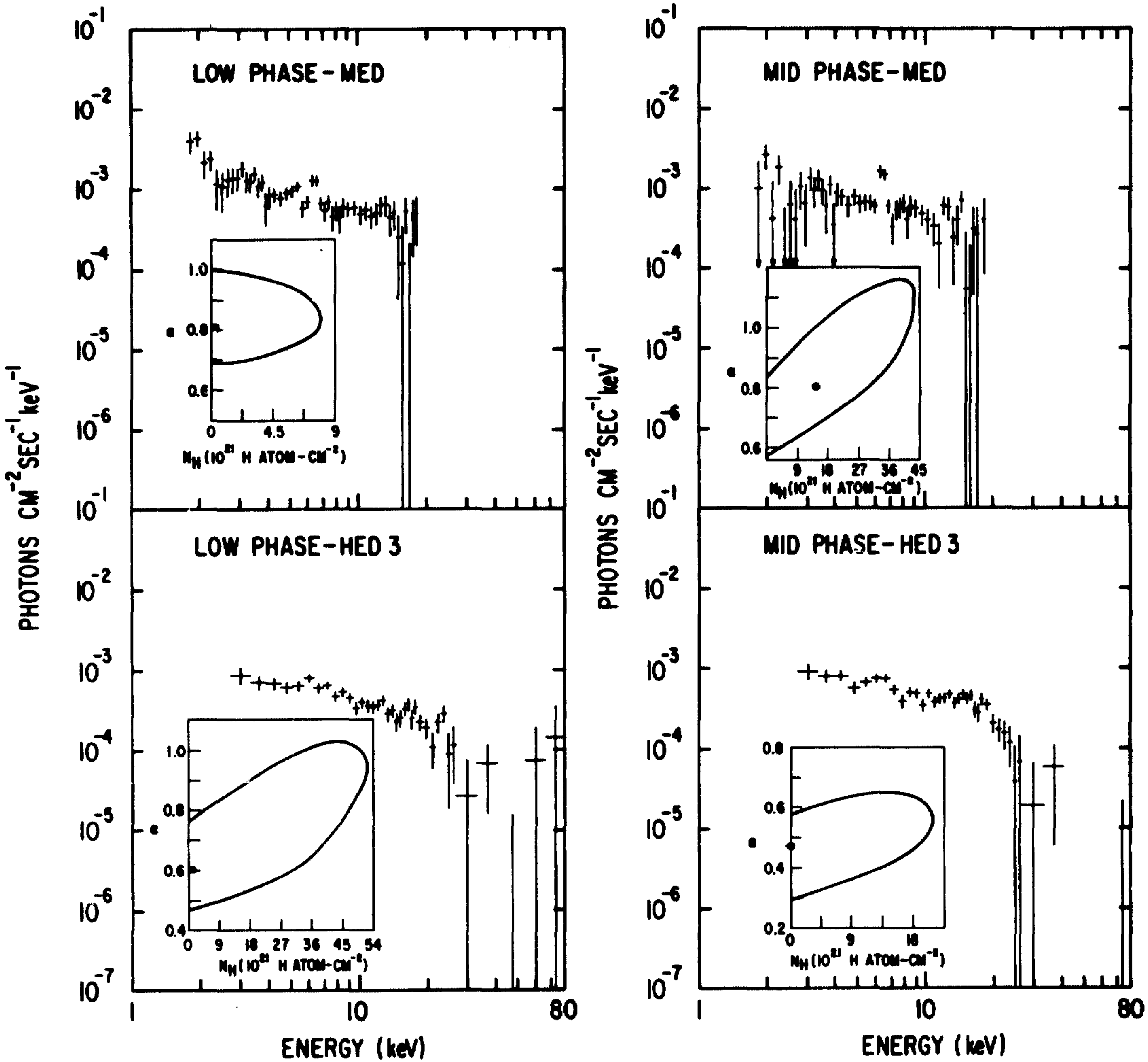
Figure 1 - The low state spectrum of Her X-1 averaged over observed binary phase. We present the best fit continuum models without a line feature superimposed on the PHA counts data, and the incident spectrum, from two detectors.

Figure 2 - Low state spectra at early and near mid binary phase. Incident spectra from an argon detector (MED) and a xenon detector (HED 3) are shown. The 1σ joint confidence contours for photon number power law index and column density are shown, along with best fit values (•).

HERCULES X-1 BINARY PHASE-AVERAGED LOW STATE SPECTRUM



HERCULES X-1 LOW STATE SPECTRA HEAO-A2



BIBLIOGRAPHIC DATA SHEET

1. Report No.: TM 79591
2. Government Accession No.:
3. Recipient's Catalog No.:
4. Title and Subtitle: DISCOVERY OF IRON LINE EMISSION IN THE HERCULES X-1 LOW STATE SPECTRUM WITH HEAO-1
5. Report Date: July
6. Performing Organization Code: 661
7. Author(s): S.H. Pravdo (U MD), E.A. Boldt, S.S. Holt, and P.J. Serlemitsos
8. Performing Organization Report No.: TM 79591
9. Performing Organization Name and Address:
   Code 661
   Cosmic Radiations Branch
   Laboratory for High Energy Astrophysics
10. Work Unit No.:
11. Contract or Grant No.:
12. Sponsoring Agency Name and Address:
13. Type of Report and Period Covered:
14. Sponsoring Agency Code:
15. Supplementary Notes: To be published in The Astrophysical Journal (Letters)
16. Abstract:

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17. Key Words (Selected by Author(s)):
18. Distribution Statement:
19. Security Classif. (of this report): U
20. Security Classif. (of this page): U
21. No. of Pages: 15
22. Price*:

*For sale by the National Technical Information Service, Springfield, Virginia 22151.

GSFC 25-44 (10/77)