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X-RAY SPECTRA OF HERCULES X-1
I. IRON LINE FLUORESCENCE
FROM A SUBRELATIVISTIC SHELL

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X-ray Spectra of Hercules X-1

I. Iron Line Fluorescence from a Subrelativistic Shell

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Abstract

The X-ray spectrum of Hercules X-1 was observed in the energy
range 2-24 keV from August 29 to September 3, 1975. A broad iron
line feature is observed in the normal high state spectrum. The
line equivalent width is 0.335 $^{+0.140}_{-0.111}$ keV and its full-width-half-
maximum energy is 2.4 $\pm$0.7 keV centered at 6.5 $\pm$0.4 keV.
Iron line fluorescence from an opaque, cool (T $\leqslant 10^6$K) shell of
material at the Alfven surface provides the necessary luminosity
in this feature. The line energy width can be due to Doppler
broadening if the shell is forced to corotate with the pulsar at
a radius of $\geqslant 8 \times 10^8$cm. Implications of this model regarding physical
conditions near Her X-1 are discussed.

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X-ray Spectra of Hercules X-1

I.   Iron Line Flourescence from a Subrelativistic Shell

Introduction

The GSFC x-ray spectroscopy experiment (CXS) on OSO-8 observed Hercules X-1 from Aug. 26 - Sept. 3, 1975. Measurements prior to "turn-on" of the source made with a xenon-filled proportional counter of the CXS are discussed elsewhere (Becker et al 1976b hereafter called Paper I). This paper presents results from a pointing argon-filled proportional counter which observed the source for $\sim$ 5 days. The iron line feature seen in the preliminary quicklook data (Pravdo et al 1976a) is now observed to be a broad "iron band" emission feature in the complete data record.

II.   Experiment and Analysis

The CXS argon filled detector has an energy range of 2-24 keV, an effective area of 36.7 cm^2, and a circular collimated field of view with FWHM of 3.34°. It is described in more detail by Becker et al (1976a). Her X-1 was in its field of view with near maximum efficiency for $\sim$ 3 complete binary orbits. The source was monitored continuously for this period, except for times of particle contamination near the satellite and earth occultations of the detector's field of view.

Spectra were compiled for each 0.1 of binary phase ($\sim$0.17d). Only "high state" spectra were compared. Those times containing intensity dips or eclipses were left for separate analysis. Spectra are identified by a Roman numeral denoting which of the three binary orbits they refer to, and an arabic numeral denoting the

beginning of the 0.1 binary phase. The time of spectrum I7 was

modified to avoid the beginning of an intensity dip. There are

nineteen spectra with 2-3 representative spectra for each high

state phase. Each spectrum contains $\gtrsim$ 10000 net counts and so is of

good statistical accuracy. The detector has 64 pulse-height channels

but high energy channels are combined to improve their statistics.

The method of spectral analysis has been discussed in Serlemitsos

et al (1975).

III. Results

The general nature of each of the spectra corresponding

to 0.1 binary phase is the same, and similar to that reported in

Holt et al (1974). They are acceptably fit by a power law model

with number index between 0.84 and 1.05 and absorption by a hydrogen

column density N_H of a few x $10^{21} cm^{-2}$. The model includes a high

energy cutoff due to energy-dependent Compton scattering in an intense

($\gtrsim 10^{12}$G) magnetic field. Boldt et al (1976) suggest that this effect

could occur at the surface of a magnetized neutron star. The effect

of the high energy cutoff is not fully seen in the limited range of

the argon detector observations since the cutoff energy is $\sim$ 25 keV.

However, the parameters of magnetic field $\sim 10^{13}$g and region Compton

scattering optical depth $\sim$ 10 fit most data.

In addition there exists considerable spectral activity in

the energy region between 5.5 and 8.2 keV. In some cases, for

example Figure 1a, a single narrow line feature centered at 6.3 keV

acceptably fits the data with a χ_r^2 (reduced) of 1.1. Without the

line, χ_r^2 = 5.8. In other spectra, for example the one shown in
Figure 1b, there is a deficiency near 6.5 keV and statically
significant line features near 5.5 and 7.4 keV. There does not
seem to be any simple correlation between spectral features and
binary phase. Within an individual binary period, the total line
equivalent width remains approximately constant with phase, whether
one or two features appear. This equivalent width is between 200
and 400 eV in most cases, and in all cases error estimates make the
equivalent width consistent with this range. Data from the first
orbit seldom (I3 and I6) need a double feature for an acceptable fit.
The second orbit data (II) are always able to be fit by a single
feature, while the third orbit data (III) have a double feature in
all spectra but one (III5). These results are summarized in Table I.
There is no apparent binary phase dependence of either the energy or
the multiplicity of the line features. All the models fit the data
acceptably except I6. Typical errors on line energies are $\pm$0.4 keV.

We examined the combined spectrum at all phases of the II
data to see if the line feature was truly narrow. In the experiment mode
setting in which these data were taken, the pulse-height channel energy
width was $\sim$ 20% higher than in the normal setting. Therefore it is less
able to resolve features with nearby energies. The combined spectrum is
fit somewhat better by a broad rather than narrow line. Also it is
consistent with two narrow lines at a maximum of $\pm$0.5 keV from the broad
line center.

The total high state spectrum was compiled for the times
during which the experiment was in the normal gain setting (I and III).
This spectrum is fit well by a model with a single broad line centered

at 6.5 keV. These 3σ confidence limits (used throughout) are placed
on the total spectrum: The line equivalent width is $0.335 \, ^{+0.140}_{-0.111}$ keV,
the line energy 6.5 ± 0.4 keV, the number index $0.91 \, ^{+0.03}_{-0.05}$, and the
absorption by a hydrogen column density of $(3.0 \, ^{+1.3}_{-1.6}) \times 10^{21}$ atoms cm^{-2}.
A similar model with a single narrow line will not fit this data.
The FWHM of the acceptable broad line is 2.4 ± 0.7 keV. The residuals
of the lines for the total spectra in both gain settings are shown in
Figure 2. Also shown is the expected residuals from narrow lines with
the same energy and equivalent width.

The pulsar period determined from this observation is
1.2378065 ± 0.0000001 sec (Paper I). After the pulsar period was
accurately determined, the spectral data for the last two orbits
(II and III) were folded separately at the period and divided into
62 independent temporal bins. A separate work (Pravdo et al 1977)
will further discuss spectral changes with pulse phase. For the
iron band emission at issue here, we divide the pulse into two regions –
"on" (P) – and "off-peak" (OP). The total OP spectrum has the same
form as the total Her X-1 spectrum. It is fit by a power law model
with a broad line near 6.5 keV, and similar number index and absorption.
However, the line equivalent width is now 0.690 ± 0.216 keV. The OP rate
is approximately half the average total Her X-1 rate. Since this measured
equivalent width is about twice the equivalent width in the total
spectrum, it is possible that all iron emission originates in the
OP region.

We can not rule out the possibility that iron band emission
occurs in at least some regions on-peak. However if the adjacent OP
regions are used as background for the P regions, the net sepctra
always show either no activity or, in some cases, deficiencies in the
iron band.

IV. Discussion

The signature of iron in the x-ray spectrum of Her X-1 has
been observed in absorption (Paper I). From this observation it was
concluded that the material which obscures the primary x-ray source
during the intensity dips (Giacconi et al 1973) contains iron in close
to the normal cosmic abundance. This material is demonstrably present
only during the small duty cycle of the dips. The particular mass transfer
from Hz Her, responsible for these dips, may be inhibited at all other
times (Gerend and Boynton 1975). Hz Her also supplies the matter from
which other regions of physical interest in the system such as an accretion
disk or an opaque Alfvén shell (McCray and Lamb 1975) are formed, as well
as the matter which is the primary energy source via the accretion mech-
anism. Each of these is expected to contain iron in the same abundance.
The question we consider is which material and what mechanism is
responsible for the observed emission feature.

Thermal iron line emission will be observed from an optically
thin plasma in the limited temperature range between 10^7 and 10^8K.
However there is no significant component of the x-ray emission from
Her X-1 with effective temperature in this range. The soft x-ray source
has temperature $\leqslant 10^6$K (Schulman et al 1975, Catura and Acton 1975).
The effective temperature of the hard x-ray spectrum is greater than
10^8K. The salient property of the emission feature is that its time-

integrated width exceeds the intrinsic detector resolution ($\sim$ 1.1 keV

at 6.5 keV). A similar feature has been observed in another binary

x-ray pulsar, Cen X-3 (Swank 1976). This again is in contrast to

previous observations of thermal line emission. For example the

iron line feature in Cas A has constant energy and is narrow on all

time scales (Pravdo et al 1976b). Charge exchange is an emission

mechanism which produces broad lines. However, this mechanism is

unacceptable because the accreting iron nuclei would have to release

essentially all of their free-fall kinetic energy in charge exchange

x-rays.

Several authors have suggested that iron line fluorescence will

be an important process in this system. The Kα fluorescence line

from cool iron normally produces a narrow line at 6.4 keV. The only

other significant iron band feature should occur near 7.3 keV, with

about 1/4 the relative intensity. This feature combines the contribution

of Fe Kβ and Ni Kα emission. These alone, however, can not explain

the width of the observed feature or the energy variability. Another

indication that fluorescence from the surface of Hz Herculis is not

the sole source of the emission is that the eclipse of

reflected x-rays from Hz Herculis is expected to last approximately

twice as long as the eclipse of the primary x-rays (Basko et al 1974).

Therefore spectra compiled at early binary phase should have considerably

less iron emission. In fact there is no apparent correlation between

the equivalent width of line features and binary phase.

The soft x-ray flux from the Her X-1 could be due to an opaque

shell of matter which accumulates at the Alfven radius of Her X-1 where

a balance exists between magnetic and gravitational forces (McCray and Lamb 1976). Basko and Sunyaev (1976) suggest that such a shell would be optically thick to Thomson scattering, and would reradiate in soft x-rays about half of the incident primary x-ray flux. Iron line fluorescence would occur in this shell. Also, since ionizational equilibrium is more dependent on photoionizational rather than collisional processes, many more ionization states of iron can be present at the same temperature. (cf. Hatchett et al 1976) This would result in a range of fluorescence line energies, which is still however, smaller than the observed range. The neutral fluorescence line at 6.4 keV is the lowest energy line, but observed features extend to $\leqslant$ 6 keV. Since iron is the major source of absorptive opacity for photons of energy $E \gtrsim$ 8 keV a large fraction of these photons ionize the iron (cf. Hatchett and McCray 1976). The fluorescence energy flux from this shell can be approximated by

$$L^f_{Fe} = 4\pi D^2 (\Omega/4\pi) \; w_K \bar{E}_K \int_8 \frac{dN}{dE} \left[1 - \exp(\sigma N_{Fe})\right] dE \qquad (1)$$

where D is the distance of Her X-1 (Forman et al 1972), w_K is the K fluorescence yield (Storm and Israel 1967), E_K the line energy, $\frac{dN}{dE}$ the photon spectral density, N_{Fe} the iron column density, σ the iron photoelectric cross section (Hubble 1971), and $(\Omega/4\pi)$ the fraction of solid angle subtended by the shell. For shell number density $5\times10^{19} cm^{-3}$, and thickness $10^5 cm$, similar to McCray and Lamb (1976) parameters, then $N_{Fe} = 1.3\times10^{20} cm^{-2}$ for cosmic iron abundance (Cameron 1973). From equation (2), L^f_{Fe} is found to be $\gtrsim 10^{35}$ erg sec^{-1} for $\Omega/4\pi) \geq 0.2$, which is approximately the observed luminosity.

If the observed feature is due to fluorescence, Doppler broadening could explain the overall energy width. The 3σ lower limit to the line width implies that the fluorescing material must have a line of sight velocity with $\beta \gtrsim 0.13$. The system orbital velocity is much lower than this value. A Keplerian accretion disk (Pringle and Rees 1972) would have to extend in to a radius of 1.4×10^7cm to obtain this velocity. This would imply a low field value ($B \approx 10^{10}$ gauss) and would rule out the Alfvén shell as the soft x-ray source (see also Scharlemann 1976). However, if a strong magnetic field from Her X-1 enforces corotation of infalling material at a radius of $\geq 8\times10^8$cm. this velocity is obtained. Changes in the mass flow pattern due to precession of the accretion disk (cf. Petterson 1974) could result in the fluorescence of matter with varying line of sight velocities, and thus a variable energy profile for this emission. Observations of the Her X-1 spectrum throughout other 35 day cycles could determine whether details of these x-ray features are periodically reproduced, as are details in the optical emission (Deeter et al 1976).

The location of the Alfven surface is determined by the strength of the stellar magnetic field. If the Alfven shell is located farther than 8×10^8cm from Her X-1 than it extends beyond the radius at which the local Keplerian velocity equals the corotation velocity. There is a question whether the magnetic field can enforce corotation beyond this latter radius.

Lamb et al. (1973) estimate that in this case the magnetic field is given by

$$B_{12} \approx (\frac{R_A}{2.6\times10^8})^{13/4} R_6^{-\frac{5}{2}} L_{37}^{x\,\frac{1}{2}} P^{-1} (\frac{M}{M_\odot})^{-\frac{3}{4}} \qquad (2)$$

where R_A is the Alfven radius, P is the rotation period and the field B_{12}, stellar radius R_6, and x-ray luminosity L_{37}^x are in power of ten notation. From equation (2) we find that the surface magnetic field is at least 6×10^{12} gauss. This lower limit is consistent with the field strength $\sim 10^{13}$ gauss estimated by Boldt et al (1976).

Iron band emission is deficient in the peak portion of the pulse light curve. The underlying continuum spectra throughout the light curve, however, are similar. The off-peak continuum emission could either escape directly through optically thin regions of the shell or be reflected by Compton scattering from opaque areas of the shell into these optically thin regions. However, if a significant amount of the continuum off-peak emission is scattered, then the optical depth for Thomson scattering must be small because of the absence of spectral distortions. A Thomson optical depth $\leq$ 3 is consistent with the observations and with estimates of McCray and Lamb. The shell itself is a source of continuum X-rays. These, however, are highly reabsorbed except in a small energy band near the iron fluorescence energy. Therefore absorption features in this continuum are not seen relative to the direct or scattered continua mentioned above.

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TABLE I. PROPERTIES OF SPECTRA BY BINARY PHASE

SPECTRA				BINARY PHASE				
	1	2	3	4	5	6	7	
I								
Line Energy (keV)	6.2	6.4	5.8	6.8	6.3	6.5	6.1	
Eq. W. (keV)	.170	.320	.104	.301	.335	.379	.274	
Line Energy			7.8			8.2		
Eq. W.			.193			.153		
II								
Line Energy	6.3	6.2	6.3	6.2	6.2	6.2		
Eq. W.	.289	.289	.312	.254	.254	.194		
III								
Line Energy	5.5	6.2	6.4	6.0	6.0	6.0		
Eq. W.	.149	.156	.306	.104	.252	.119		
Line Energy	7.4	7.4	8.2	7.2		7.0		
Eq. W.	.338	.184	.171	.153		.230		

Figure Captions

Figure 1a. Hercules X-1 spectrum II 2 as defined in text.

b. Hercules X-1 spectrum III 1 as defined in text.

Figure 2. Residuals above continua for data sets I and III (above) and II (below). The histogram is the residuals expected if two narrow lines at 6.5 and 8.0 keV were present with the same equivalent width as the broad feature.

PHOTONS $(cm^{-2} sec^{-1} keV^{-1})$

ENERGY (keV)

ENERGY (keV)

10^2

10

10^2

10

10^{-1}

10^{-2}

10^{-3}

10^{-4}