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ABSTRACT

We present observations of Cygnus X-1 with the solid-state spectrometer on the Einstein Observatory. The X-ray spectra of two intensity dips viewed near superior conjunction did not exhibit increased photoelectric absorption. Rather the data support a model in which an increase in the electron scattering optical depth modifies both the observed spectrum and the intensity. The characteristic temperature of the intervening material is $\gtrsim 5 \times 10^7$ K. These measurements were in part simultaneous with observations by IUE. The ultraviolet spectrum and intensity remained relatively constant during an X-ray intensity dip.

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I. INTRODUCTION

X-ray observers have detected from Cyg X-1 a number of short-lived ($\sim$ hours) intensity decreases which occur preferentially near superior conjunction (Li and Clark 1974; Mason et al. 1974; Holt et al. 1979a). These have been characterized as photoelectric "absorption dips" caused by sudden increases in the line-of-sight column density of cool material. We describe two such events which were observed with the solid-state spectrometer (SSS) on the Einstein Observatory. In addition, the ultraviolet spectrometer on the International Ultraviolet Explorer (IUE) observed Cygnus X-1 during one of these observations.

II. X-RAY OBSERVATIONS

Cygnus X-1 was observed with the SSS on three occasions--April 26, May 9, and May 13, 1979. The SSS is a cryogenically-cooled Si(Li) detector at the focus of the Einstein Observatory X-ray telescope. It has an energy resolution of $\sim$ 160 eV FWHM over the range 0.5 - 4 keV, and a 6 arc-min field of view. Additional information regarding this detector can be found in Holt et al. (1979b) and references therein. Data were simultaneously obtained in the 2-15 keV energy range with the Monitor Proportional Counter (MPC) which is co-aligned with the SSS (Giacconi et al. 1979).

Two of the observations occurred near superior conjunction (Bolton 1975) and the X-ray light curves are shown in Figure 1. In both cases an intensity dip is apparent near superior conjunction ϕ = 0; i.e. when the X-ray object is on the far side of the O star. The intensity decreases are more pronounced in the lower energy SSS range than in the MPC.

Spectral analysis is performed by folding typical models through the detector response function and comparing the resultant to the data via the χ^2 test (see also Holt et al. 1979b). The systematic uncertainty in the response function was approximated by an additional 4% error in quadratures with the statistical error for each channel; this did not change the best-fit values, but had the effect of making the best-fits statistically acceptable. The χ^2 values in Table 1 include this added uncertainty. Figure 2 shows the count rate spectra for three different intensity states which, in order of increasing intensity, are:

1. The larger dip seen on May 9,
2. The smaller dip seen on May 13, and
3. The "normal" state on May 9.

We find that in all cases the best fit one-component model is a power law with some photoelectric absorption (Fireman 1974). The power law index varies inversely with the intensity, i.e. the lower the intensity, the flatter the spectrum becomes. Table 1 lists the parameter values for this model. The slope of the normal spectrum is in good agreement with the higher energy measurements of Rothschild et al. (1977) although the intensity is higher by $\sim$ 50%. If we fix the power law index at the normal state value and attempt to fit the dip spectra by varying only the column density of cool material, the values of χ^2 are a factor $\sim$ 10 larger than obtained by allowing the slope to vary. It is formally possible to synthesize the dip spectra with partial obscuration by cold material, but the size of the source region is so small relative to the binary separation that we do not consider this explanation plausible for the Cyg X-1 system. Thus a characterization of these intensity decreases as "absorption dips" would be incorrect (see also Parsignault et al. 1976). We note that a detector with lower spectral resolution or a higher low energy threshold would have difficulty distinguishing between increased photoelectric absorption or a flattening of the continuum, since the maximum deviations from the absorption model occur at energies less than 2 keV. The observation of April 26 extended over the phase range ϕ = 0.67 - 0.71. There was no significant intensity dips and the normal state spectrum measured at this phase was consistent with that seen near superior conjunction (see Table 1).

We tested for the presence of an additional soft X-ray component with $kT_{soft} \sim 0.1$ keV. Since the lowest analyzed pulse-height-equivalent energy is $\sim$ 0.8 keV it is impossible to unambiguously identify such a component, or to deduce whether it is optically thick or optically thin emission. Nevertheless, its inclusion leads to significant reductions of the χ^2 value in several spectra (Table 1), and it could be present with approximately constant luminosity in all the observed spectra. The luminosity in this emission could be as large as 4×10^{37} erg sec^{-1}, for a source distance 2.5 Kpc, assuming the low energy absorption is unrelated to the source.

We can place an equivalent width upper limit of $\sim$ 20 eV (or $\lesssim 10^{-2}$ photons cm^2 sec^{-1}) for narrow silicon ($\sim$ 1.7 keV) or sulphur ($\sim$ 2.4 keV) line emission.

III. ULTRAVIOLET OBSERVATIONS

Four ultraviolet spectra of HDE226868 were obtained with IUE; three on May 9 and one June 10, 1979. The May 9 times are indicated by "IUE" on Figure 1. The first and second exposures bracket the larger X-ray intensity dip; the end of the first exposure may have partially overlapped with the X-ray event. The X-ray flux was at least 20% less during the first exposure than after the X-ray dip (Figure 1). All observations were made in the low resolution mode with the short wavelength camera (SWP-Boggess et al. 1978); the wavelength covered was about 1200-1900 Å at a resolution of 6-7 Å.

The orbital phases of the start of these four observations are 0.031, 0.067, 0.092, and 0.762, respectively in chronological order. We found no significant differences among the four spectra with respect to flux level and features (an upper limit of $\sim$ 500 km s^{-1} is obtained for velocity changes compared to the maximum line of sight velocity of 72 km s^{-1} (Bolton 1975)), and they are also consistent with the spectrum obtained with IUE by Dupree et al. (1978) except that line identifications have been improved in the current work. No significant line emission is seen. The spectra are absorption line spectra with probably identifications summarized in Table 2.

The Si IV and C IV lines show central Doppler shifts of -360 ± 100 km s^{-1} and -565 ± 100 km s^{-1} respectively, averaged over the observations of May 9. The averaged values of the extreme shortward wavelength shift of the Si IV and C IV lines are -1570 km s^{-1} and -2270 km s^{-1} respectively. These values are indicative of the stellar wind from the optical star.

IV. DISCUSSION

The intensity dips probably occur when a blob of additional material is found between the X-ray source and the observer. The occurrence of many dips near superior conjunction suggests that material is injected, or prominences are formed on the accretion disk, along the line connecting the binary companions (e.g. Murdin 1976).

The spectra during the dips can be used to measure the temperature of the intervening blobs. Temperatures, $T_{BLOB} \lesssim 10^6$ K, are ruled out since photoelectric absorption by cool material can not describe the dip spectra below $\sim$ 2 keV. For 10^6 K < T_{BLOB} < 5×10^7 K, photoelectric absorption by ionized material can create a spectrum in which the deficiency at $E \lesssim$ 2 keV is relatively less for ionized than for cool material. We approximated this model with three absorption edges due to the iron L edge ($\sim$ 1.1 keV), the silicon K edge ($\sim$ 2.1 keV), and the sulphur K edge ($\sim$ 2.6 keV). It also does not describe the data well (see Table 1). Finally, if $T_{BLOB} > 5 \times 10^7$ K there would be no photoelectric absorption in the SSS energy range and the spectral change must be associated with free-free absorption and/or electron scattering. Note that X-ray heating of the blob could bring it up to this temperature even if it were initially much cooler.

In the standard model (Shapiro, Lightman, and Eardley 1976) soft X-rays ($kT_{soft} \sim$ 0.1 keV) are generated within the Cygnus X-1 accretion disk. These are then Compton-scattered into hard X-rays by hotter electrons ($kT_e \sim$ 50 keV) in the gas surrounding the disk. The luminosity in the soft X-ray component need be only $\lesssim$ 1% of the total X-ray luminosity. While these observations support the existence of such a component, the intensity is poorly determined; it could be $\sim$ 100 times more than that in the model (see also Garmire and Ryter 1975). Recent measurements of the hard X-ray spectrum have been modelled using the calculations of Sunyaev and Titarchuk (1979), and indicate an electron temperature, $kT_e = 27$ keV, and a Compton scattering depth, $\tau_{es} = 5$ (Sunyaev and Trumper 1979). The Comptonization models predict that for photon energies, $kT_{soft} < E < kT_e$, the spectrum is nearly a power law with slope dependent only on T_e and τ_{es}.

The spectra obtained during the intensity dips are best described as power laws in the energy range 0.8 - 4 keV. Analysis of the MPC data indicates that the spectrum steepens again to its normal state slope above $\sim$ 5 keV (Grindlay 1979). Thus a two-power law model plus a low temperature component can describe the 0.9 - 15 keV spectrum. The Comptonization model mentioned above and photo-electric absorption alone can not explain the observed spectra. Free-free absorption might become important if the blob density is sufficiently high. In this case the blob becomes an X-ray emitter, and the work of Felten and Rees (1972) indicates that a spectral break will occur at a transition energy, E_t, such that the free-free optical depth, $\tau_{ff}(E_t) \gtrsim \tau_{es}{}^{-1}$. If we assume, for example, that τ_{ff} (5 keV) $\sim$ 0.1 and $kT_{BLOB} \sim 5$ keV then the blob would have a density, $n \sim 2 \times 10^{22}$, and a linear extent of only 600 cm. It seems unlikely that such a hot, dense, thin slab could be formed or that it could exist for several hours.

A remaining possibility is that the X-rays during the intensity dips have undergone a second Comptonization by electrons in the blob. Since the spectrum hardens for $E \lesssim 5$ keV, the blob must have $kT_{BLOB} \gtrsim 5$ keV. If $kT_{BLOB} \lesssim kT_e$, however, the spectral hardening should continue up to $E \sim kT_e$, which is not observed. These general arguments indicate that $kT_{BLOB} \sim 5$ keV, and the electron scattering depth in the blob is significant ($\gtrsim$ 1). Detailed calculations are needed to determine whether the observed spectra can be formed in this way.

The absence of UV variations during the time overlapping the X-ray intensity dip indicates that the UV emission region is separate from either the X-ray emission region or the intervening blob, and that the coupling between X-ray and UV variations, if any existed, would be on a time scale greater than hours. This is not so surprising since the UV spectral features of this object are not dissimilar to those in other stars of this spectral type, and the contribution of the UV photons from the accretion disk and the gas stream is probably rather limited. Finally, we have been unable to detect spectral variability as a function of orbital phase (comparing phases ~ 0 to ~ 0.7) in either the X-ray (Buff and McCray 1974) or UV spectra (Hatchett and McCray 1977).

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TABLE 1

CYGNUS X-1: Parameters of Power Law Model

Date	Orbital Phase[a]	Intensity State	Normalization	Number Index	N_H[b] H-Atoms cm^{-2}	χ^2/Degrees of Freedom
April 26	0.69	Normal	1.21 ± 0.03	1.47 ± 0.02	2.2 ± 0.2	67/57
		[c]Normal	1.27 ± 0.05	1.51 ± 0.03	2.7 ± 0.4	64/55
May 9	0.07	Normal	1.13 ± 0.03	1.41 ± 0.02	2.2 ± 0.2	75/57
		[c]Normal	1.13 ± 0.03	1.41 ± 0.02	1.8 ± 0.2	75/55
May 9	0.04	Larger Dip	0.162 ± 0.006	0.26 ± 0.03	2.0 ± 0.2	123/57
		[c]Larger Dip	0.211 ± 0.012	[illegible].45 ± 0.05	4.5 ± 0.6	86/55
		Larger Dip	0.624 ± 0.006	[d]1.41	11. ± 1.0	1060/57
		Larger Dip	0.761 ± 0.006	[d]1.41	e	330/52
May 13	.84	Normal	1.15 ± 0.03	1.42 ± 0.02	0.2 ± 0.2	76/57
		[c]Normal	1.21 ± 0.03	1.46 ± 0.02	0.6 ± 0.3	74/55
May 13	.83	Smaller Dip	0.466 ± 0.04	0.87 ± 0.08	0.2 ± 0.2	90/57
		[c]Smaller Dip	0.714 ± 0.126	1.20 ± 0.14	3.9 ± 0.2	73/55
		Smaller Dip	0.874 ± 0.018	[d]1.44	3.8 ± 0.3	131/58

a) Phase relative to superior conjunction (Bolton 1975)

b) Units 10^{21} H-atom cm^{-2}; systematic absolute uncertainty of $\sim 2 \times 10^{21}$ H-atom cm^{-2} (Holt et al 1979)

c) Models include a thin bremsstrahlung component with kT_{soft} = 0.1 keV

d) Index held fixed

e) Ionized model (see text)

Table 2

Far-Ultraviolet IUE Spectrum of Cygnus X-1 - HDE 226868

Wavelength or Wavelength region	Probable Contributing Ions	Laboratory Wavelength
1240-1280Å	C I, Si II, Si III, S I, Fe II	---
1300-1305Å	Si III + ?	---
1383-1405Å	Si IV	1393.755 + 1402.770
1500-1510Å	C I, Si II, Si III, Fe III	---
1538-1553Å	C IV	1548.185 + 1550.774
1558-1574Å	Fe II	---
1600-1626Å	Fe II, Fe III	---
1631-1633Å	Fe II	---
1709-1735Å	N IV, Fe II	---
1850-1865Å	Al III, Fe II, Fe III	---

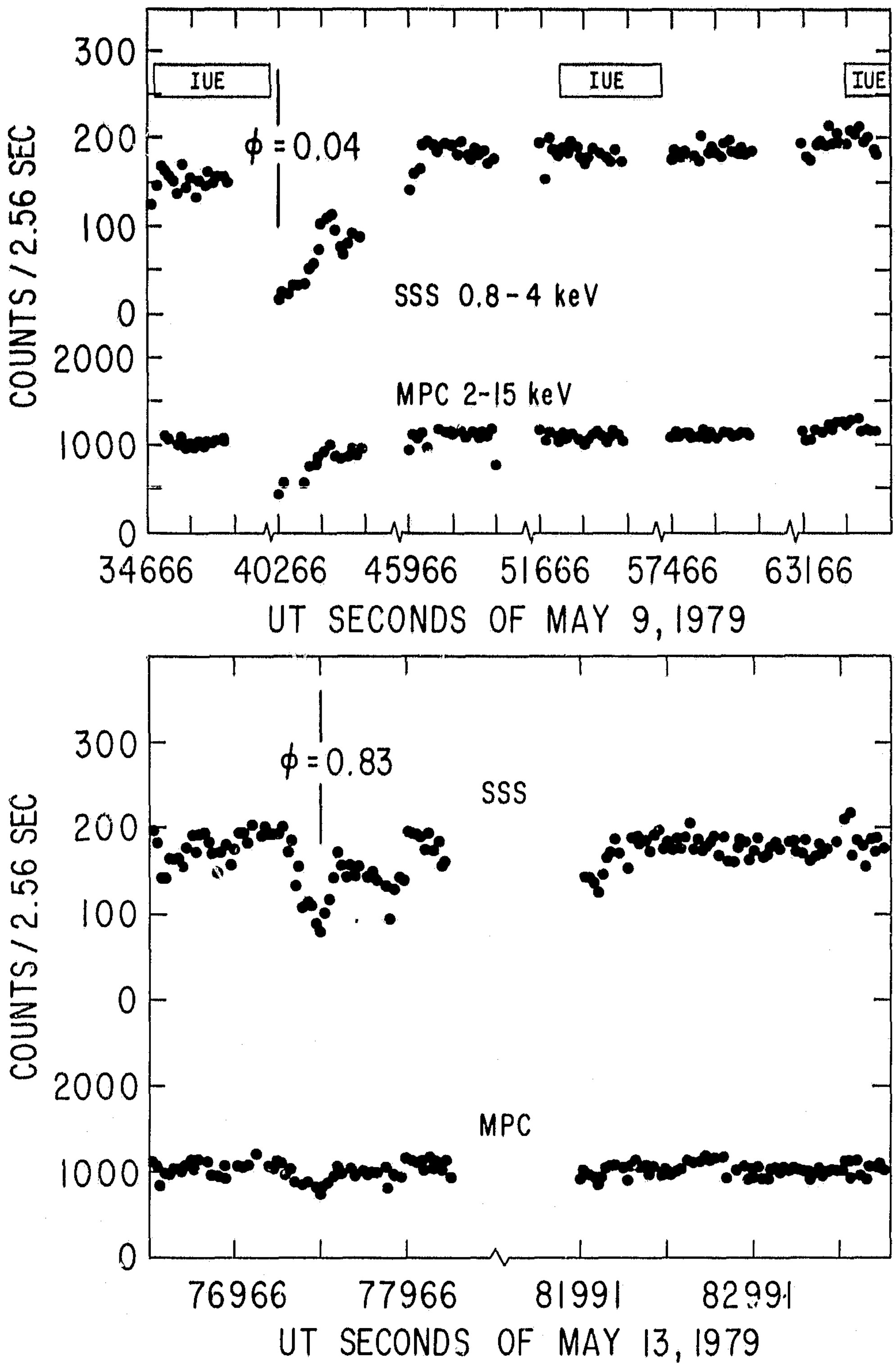
FIGURE CAPTIONS

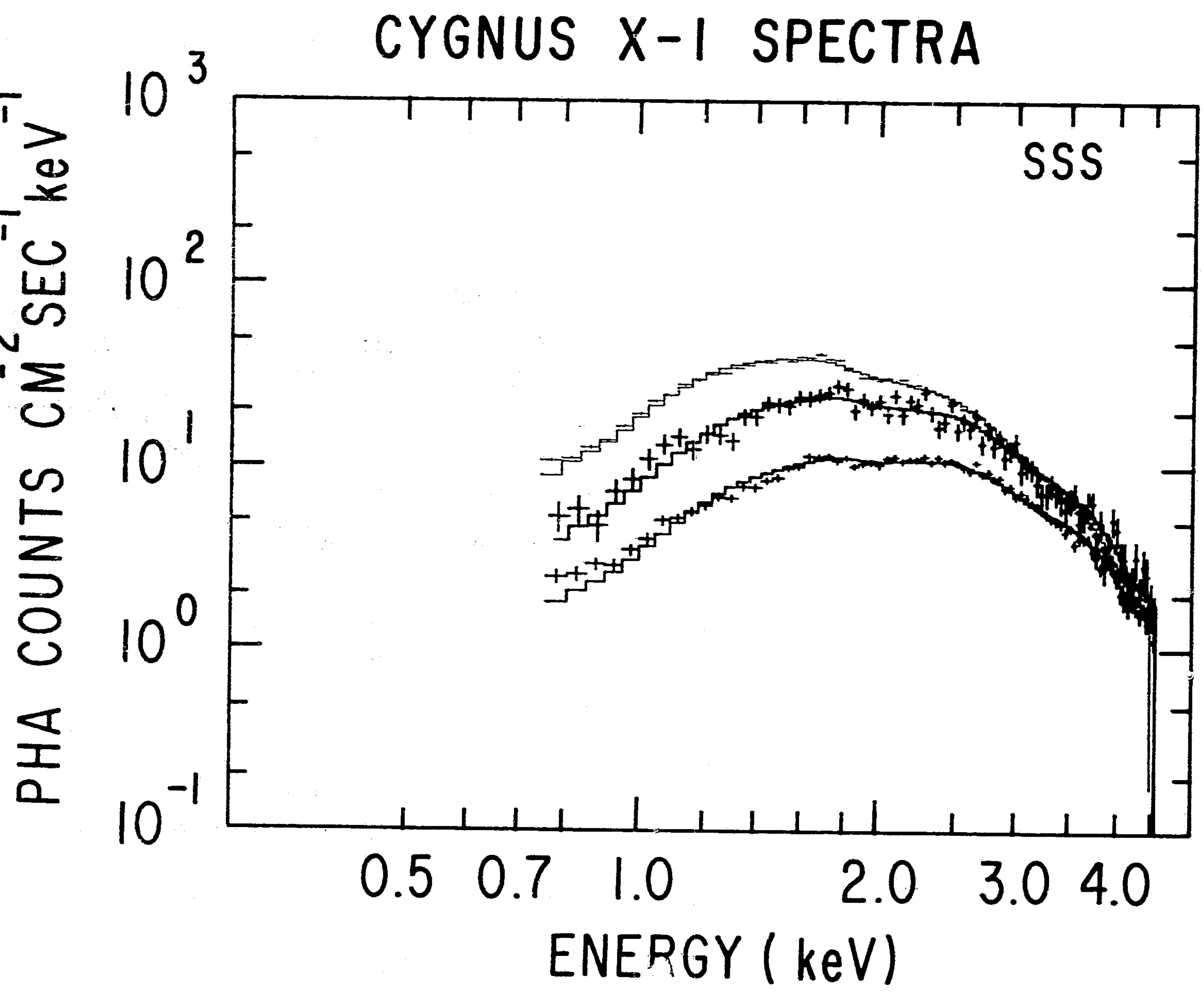
Figure 1 - The X-ray light curves of Cygnus X-1 during two observations near superior conjunction. The orbital phase calculated from the ephemeris of Bolton (1975) is indicated for each of the intensity dips. In addition, the times during which IUE observations were performed are indicated by "IUE". Note that the time axis is expanded by a factor of 4 in the lower plot.

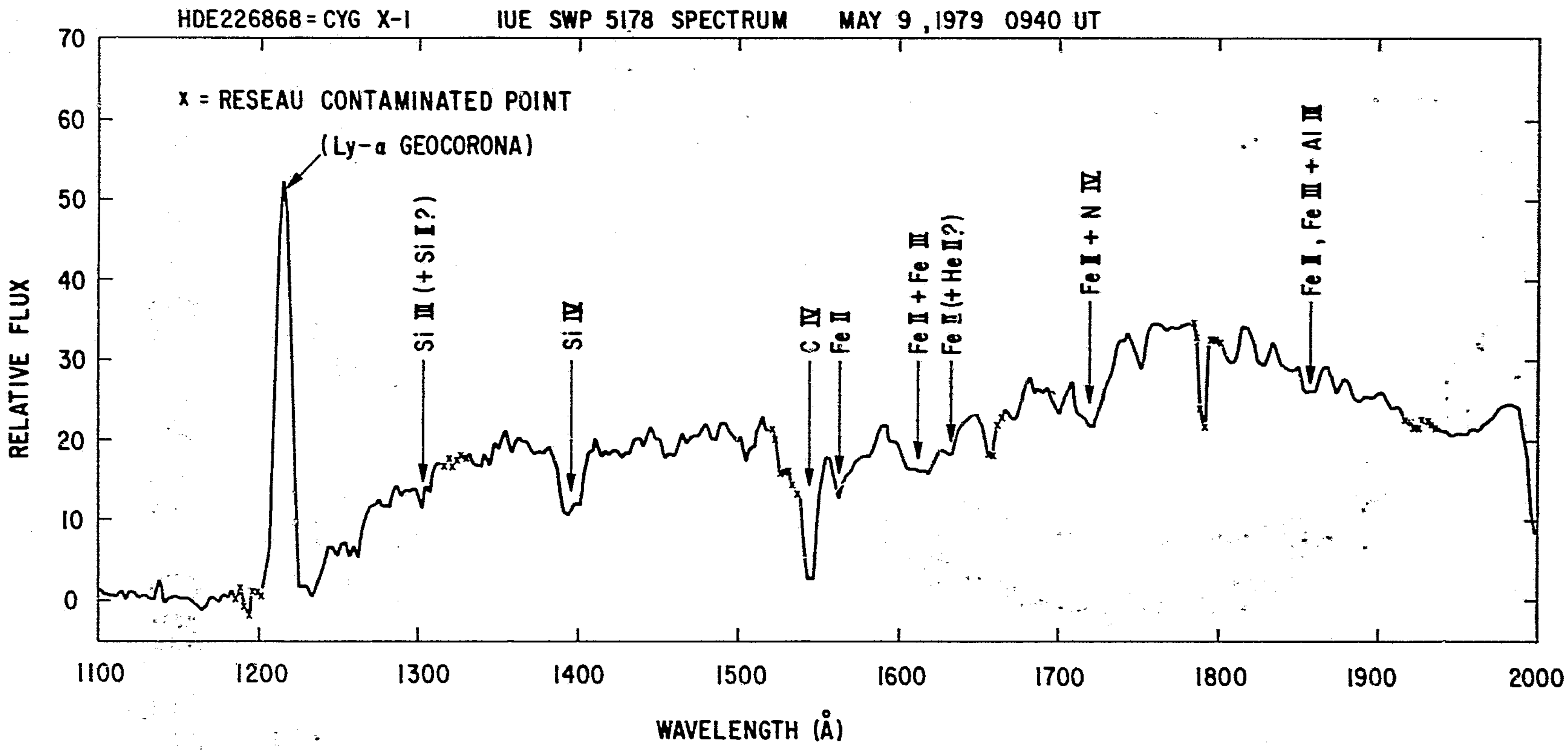
Figure 2 - Three count rate spectra of Cygnus X-1 obtained during the larger dip (May 9), the smaller dip (May 13), and the normal intensity state (May 9)--in order of increasing intensity. Superimposed on the data are power law model histograms whose parameters are listed in Table 1.

Figure 3 - Only those lines clearly identified are indicated in this spectrum obtained with the first IUE observation of May 9. For possible identification of other features, see Table 2. The abscissa may be translated to absolute flux through the use of the relationship published by Bohlin and Snijders (1978), which is currently being updated. The abscissa unit, 10., at 1500 Å corresponds approximately to 1.2×10^{-13} erg cm^{-2} Å^{-1} The absolute flux at the source can be estimated from the interstellar reddening measurements of Wu, van Duinen, and Hammershlag-Hensberge (1976).

CYGNUS X-I LIGHT CURVES




CYGNUS X-1 SPECTRA
SSS
PHA COUNTS CM^{-2}SEC^{-1}keV^{-1}
10^3
10^2
10^1
10^0
10^{-1}
0.5
0.7
1.0
2.0
3.0
4.0
ENERGY (keV)


HDE226868 = CYG X-1
IUE SWP 5178 SPECTRUM
MAY 9, 1979 0940 UT
x = RESEAU CONTAMINATED POINT
(Ly-α GEOCORONA)
Si III (+Si II?)
Si IV
C IV
Fe II
Fe II + Fe III
Fe II (+He II?)
Fe II + N IV
Fe II, Fe III + Al III
RELATIVE FLUX
WAVELENGTH (Å)
0
10
20
30
40
50
60
70
1100
1200
1300
1400
1500
1600
1700
1800
1900
2000

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16. Abstract

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