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THE VARIABLE IRON LINE IN CYGNUS X-3

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ABSTRACT. Cygnus X-3 was observed with the GSPC on board EXOSAT on several occasions, one observation lasting for 7 orbital cycles. The width W and centroid energy E of the iron emission feature near 6.7 keV show a smooth, correlated, sinusoidal-type modulation, the iron line being widest and E being lowest just before X-ray maximum. The line profile may show a low-energy wing, but apart from this does not deviate strongly from a symmetric, Gaussian-type shape. The continuum at higher energies than the line is not completely smooth, but shows 'bumps' which remain stable in time. Two possible explanations are discussed for the correlated variation of E and W as a function of orbital phase.

1. INTRODUCTION

Cygnus X-3 is an enigmatic X-ray binary of which both the primary energy source (accretion onto a compact object or a Crab-like pulsar (1)) and the modulating mechanism (which produces the smooth, 4.8 hr period X-ray binary orbital light curve) are not yet understood.

The many qualitatively different models which have been put forward for this source all involve scattering of the X-ray photons generated near a compact object into our line of sight, where the scattering medium has variously been proposed to be a large cocoon surrounding the entire system (2,3), a stellar wind (4,5), a shock between the two binary components (6), the surface of the companion to the X-ray source (1) or an accretion-disk corona (7).

The X-ray spectrum of the source is complex. The continuum must be composed of different components, some or all of which vary as a function of 4.8 hr phase and on longer timescales, and it has been interpreted in different ways by various authors (8,9,7,10). In addition, the source shows a very strong iron emission feature between

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6 and 7 keV (11,12) - in fact, with its 0.02 - 0.06 photons/cm^2 s, Cyg X-3 is the brightest object in the iron-line night sky.

We might hope, therefore, to obtain an insight in the various emitting regions in the system by carefully studying the variations of this iron feature as a function of orbital phase. Previous studies using standard proportional counting detectors (11,12,8,9,7,10) have shown that the flux in the line approximately follows the 4.8 hr continuum flux variations, but not the long-term variations, so that the equivalent width increases strongly during extended low-intensity states of the source, but only slightly in the minima of the 4.8 hr light curve. Line centroid energies have variously been quoted from these studies as between 6.3 and 6.8 keV, with a tendency towards lower energies during light curve maximum (12,8). Line widths of between 0.5 and 1.5 keV (FWHM) have been claimed and in two cases there was a suggestion of the line being wider during X-ray maximum (12,10).

In this paper we present results of a study of the iron line in Cyg X-3 with the EXOSAT gas scintillation proportional counter (GSPC). The higher resolution of this instrument as compared to normal proportional counters and the extended pointing capabilities of EXOSAT have allowed for the first time to measure accurately the phase-dependence of line width and line centroid energy, and to obtain information about the shape of the line profile.

2. OBSERVATIONS

We have observed Cyg X-3 with EXOSAT for ~ 7 binary cycles on days 184-186, 1983, for ~ 2.5 cycles on day 299, 1983 and on 9 other occasions (up to day 272, 1984) for shorter intervals. The light curve of the 7-cycle observation is shown in Figure 1.

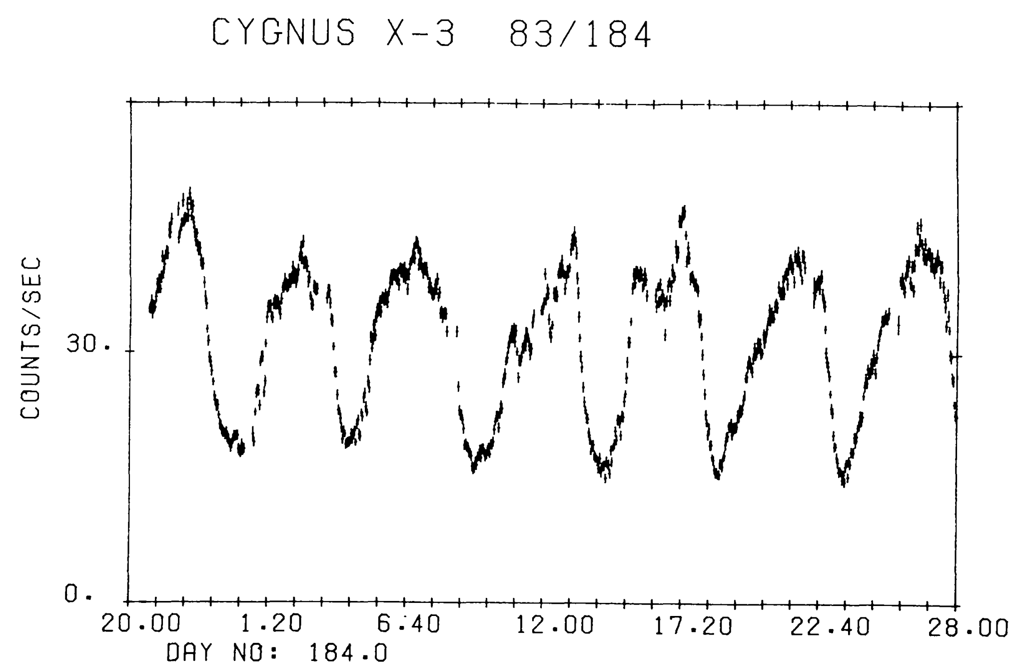

Figure 1. 2-16 keV EXOSAT GSPC light curve of Cygnus X-3. Data are background subtracted and were averaged into 2 min. bins.

Examples of the spectra obtained during this observation, constructed by collecting data during the light curve maxima and minima are given in Figure 2. The increase in equivalent width of the line near 6.7 keV in the 'minimum' spectrum is evident. The feature near 4.7 keV is instrumental; it is due to the L-edge of the Xenon detector gas.

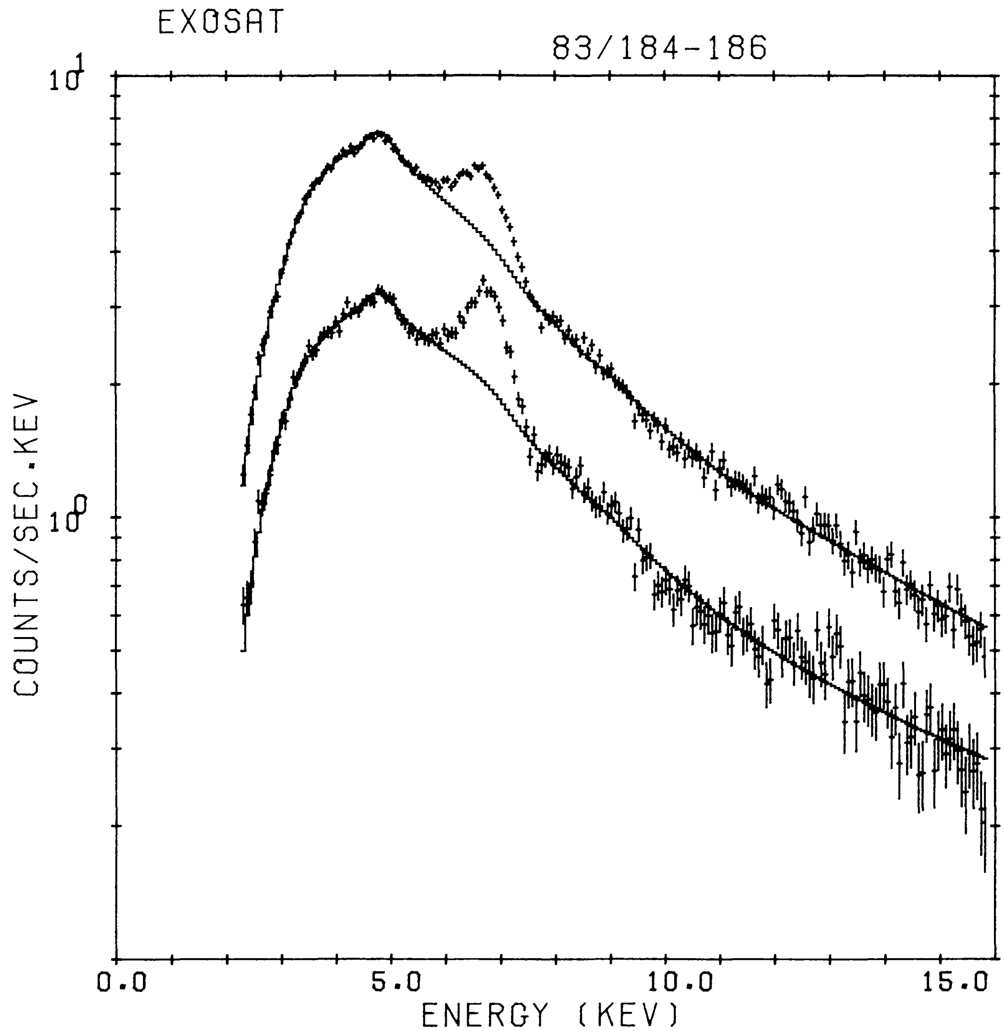

Figure 2. GSPC spectra of data collected inside phase bins $0.4<\phi<1.0$ (maximum) and $0.9<\phi<1.0$ (minimum), where phase zero is near light curve minimum. The effective observing time of each background subtracted spectrum is ~ 200 min.

3. ANALYSIS AND RESULTS

The data obtained during the two longest observations (184/83 and 299/83) were folded modulo the 4.8 hr period and divided into 10 equal phase bins. We then constructed a GSPC spectrum for the data in each phase bin. All spectra were fit with a three-component continuum model, which from previous work is known to be necessary to provide an adequate fit to the X-ray continuum in Cyg X-3 (8,9,7), plus a Gaussian iron line. As continuum components we adopted a black body spectrum with kT ~

1.2 keV, a power law to model the high-energy part of the spectrum and a 0.3-0.5 keV thermal component as a representation of the soft excess (7). The instrumental feature near 4.7 keV was described in the standard way as a Gaussian emission feature of known strength. In order to obtain as unbiased an estimate as possible of the iron line parameters, all continuum and line parameters were allowed to freely assume the values corresponding to the best fit. Typical reduced chi-squared was 1.4 for about 80 degrees of freedom (2-16 keV). Tests in which we forced continuum parameters to certain fixed values showed that the line parameters are only weakly dependent on the continuum fit

The iron line parameters determined in this way have been plotted in Figure 3 as a function of orbital phase together with the average 2-15 keV light curve.

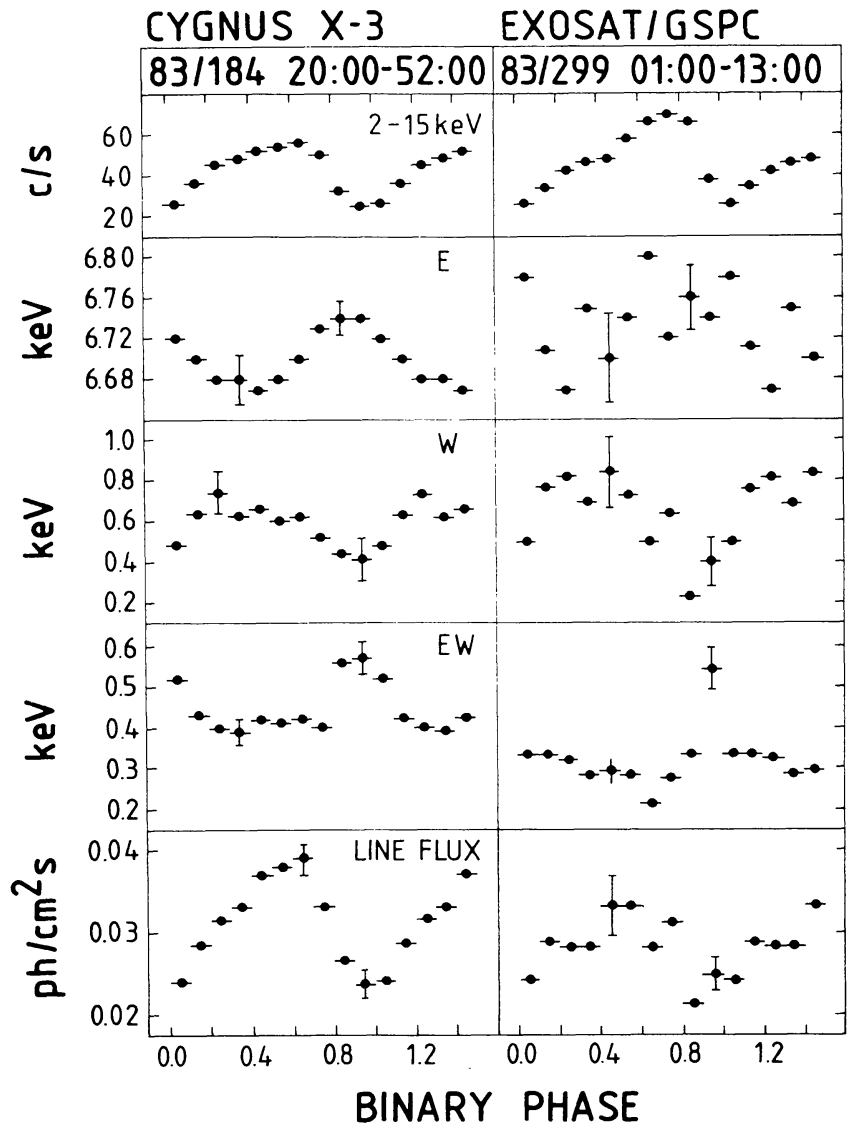

Figure 3. Average total 2-15 keV flux, iron line centroid energy E, full width half maximum line width W, equivalent width EW and line flux in photons/cm^2 s as a function of orbital phase. Errors were determined by projection of the χ^2+3.5 error ellipsoid onto the coordinate axes in parameter space.

The 184/83 observation shows a clearly defined, smooth sinusoidal-like variation of line centroid energy, line width and line flux, whereas the equivalent width may show a sharper-peaked modulation. The 299/83 observation, which is much shorter, shows larger statistical fluctuations, but may serve as a confirmation of these results. Previous indications (12,8,10) of lower line energy E and greater width W near light curve maximum are confirmed, however, we now see that the shape of the X-ray light curve, with its slow rise to maximum and much steeper decrease is not mimicked exactly by W and -E. The maxima and minima of W and E coincide, but they appear to precede the light curve maximum and minimum. The phase dependence of the flux in the line, on the other hand, does closely follow the total flux, although it is not as deeply modulated, which shows up in an increase of the equivalent width near light curve minimum.

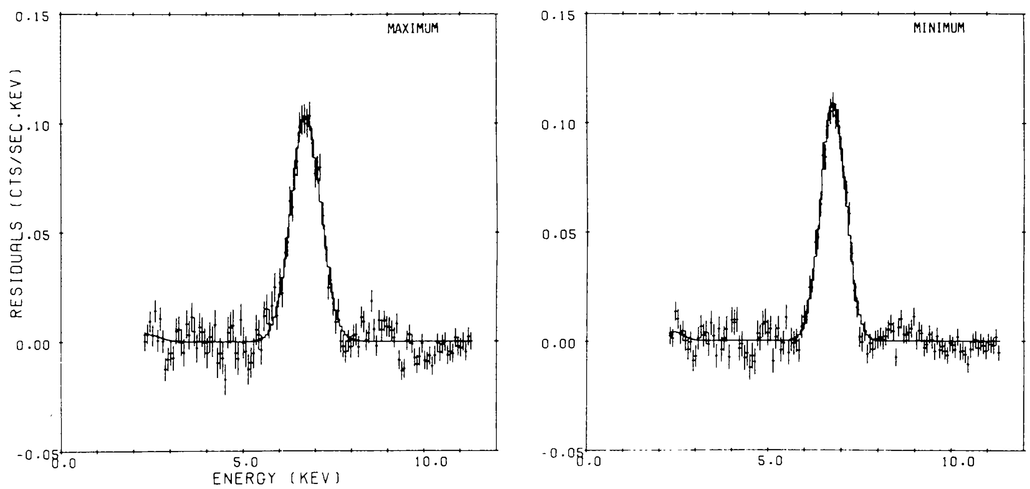

Figure 4. Line profiles observed during phase intervals $0.2<\phi<0.3$ and $0.9<\phi<1.0$. The change in line width is obvious.

We have analysed the data contained in the remaining, shorter observations in a similar way. The line intensity is roughly correlated with overall (phase averaged) source intensity, but not sufficiently to prevent a decrease in line equivalent width when the source becomes brighter; the low-state spectra follow this general behaviour. The other line parameters generally fit in well with the results presented for 184/83 and 299/83, with some exceptions. One such exception, a very wide line observed on day 352/83 ($W \sim 1.2$ keV) is illustrated in Figure 5. This anomalously wide line is not correlated with any evident anomaly in light-curve or continuum spectrum shape.

As can be seen in Figures 4 and 5, the observed line profiles do not deviate very much from a simple Gaussian shape. In most cases, a low-energy wing is visible, which becomes much clearer if we add up all data in the 83/184 observation to improve statistics (Figure 6).

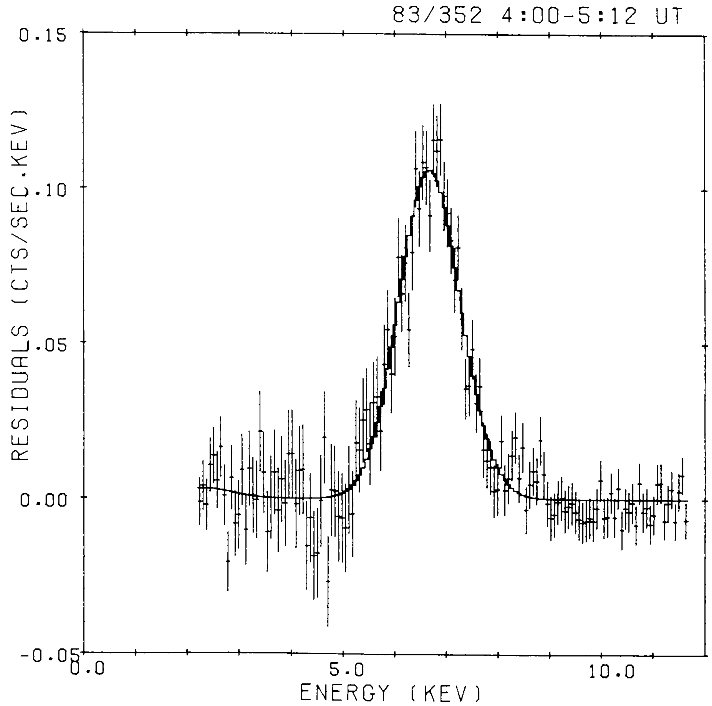

Figure 5. An anomalously wide line profile (FWHM ~ 1.2 keV) observed during light curve maximum on day 352, 1983.

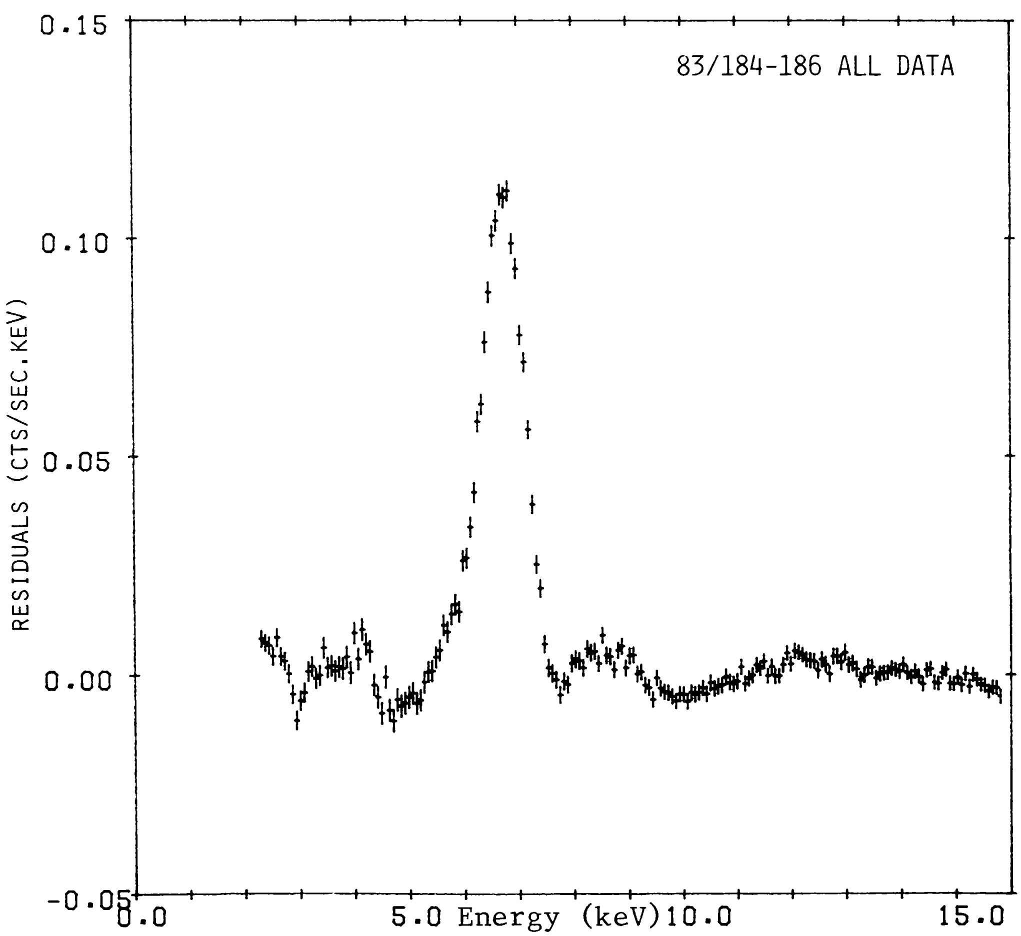

Figure 6. The phase-averaged residual spectrum of the 83/184-186 observation.

Contrary to the other line parameters, however, this low energy wing is found to be dependent on the continuum fit, in particular on the modelling of the soft excess. This soft excess, together with the 4.7 keV instrumental feature combine to make the details of the spectrum at energies below 5 keV somewhat uncertain. The structure at higher energies than the line - which can be described as a 'bump' in the spectrum with a centroid energy near 9 keV (which is too high to identify this bump with an indisturbed iron Kβ feature) and a broad maximum between 11 and 16 keV, or alternatively in terms of 'dips' or edges - is quite stable. Looking back to published proportional counter spectra (9), we can indeed identify the same structures in spectra taken in 1976.

4. DISCUSSION

We have not yet attempted to extensively model the line-parameter variations presented in this paper. There are two obvious possible qualitative explanations for the centroid energy decrease and width increase in the line near light curve maximum:

1. The line consists of two components, a high-energy component near 6.7 keV, which could arise from thermal emission from a disk or near the compact object, and a fluorescent component near 6.4 keV generated at the irradiated surface of the companion or at the inner side of a bulge in the disk's rim (located near the impact point of the gas stream feeding the accretion). Geometrical effects would cause a variation in the strength of the fluorescent component in qualitative accordance with the observed line variations.

2. The variations in the line are entirely caused by variations in the Comptonisation of the line photons by cool electrons (Comptonisation is anyway, from the observed line widths, likely to occur). The observed variations would then require an increase of effective Compton scattering depth near light curve maximum. In a simple approximation (13), one would expect a highly asymmetric line profile with a narrow core in this case.

Very preliminary two-component fits to some representative line profiles seem to indicate that explanation 1. is consistent with the data: the low-energy component varies strongly in intensity, while the high-energy component remains stable. The high-energy component comes out to be rather narrow, however, which might also indicate that it is dominated by an unresolved narrow line core as mentioned in 2.

Further work is clearly required. However, from the above, it is already clear that the ability to accurately measure the iron-line parameters as a function of orbital phase provides us with a new probe into the Cygnus X-3 system.

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