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A Study of Ultraviolet Spectroscopic and Light Variations in the X-ray Binaries LMC X–4 and SMC X–1*

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Summary. Low-resolution IUE spectra of the massive X-ray binaries LMC X-4 and SMC X-1 have been obtained between 1200 and 3200 Å at several epochs in August 1979 and April 1980. Comparison of these observations with theoretical light curves for an X-ray heated tidally distorted star indicate the existence of a disk around the compact star.

The resonance-line doublets of N V, C IV and Si IV show marked changes with orbital phase, being particularly weak when the X-ray source is in front of the primary. These changes can be understood in terms of an anisotropic ionization structure in the expanding atmosphere of the primary caused by the presence of the X-ray source companion.

Key words: X-ray sources – close binaries – UV spectra

I. Introduction

The binary X-ray sources LMC X-4 and SMC X-1, the first to have been discovered in external galaxies, are of particular interest because of their large X-ray to optical luminosity ratios (for massive binaries) and their peculiar double-wave optical light curves (Chevalier and Ilovaisky, 1977; van Paradijs, 1977; van Paradijs and Zuiderwijk, 1977; see also Ilovaisky, 1980; Chevalier et al., 1981).

Both sources show X-ray eclipses with orbital periods of 3.89 d (SMC X-1) and 1.41 d (LMC X-4), respectively. SMC X-1 is known to show extended low states in its X-ray emission (Schreier et al., 1972; Cooke et al., 1978; Tuohy and Rapley, 1975; Bonnet-Bidaud and van der Klis, 1981). Recently, a 30.5 day periodicity was discovered in the X-ray intensity of LMC X-4 (Lang et al., 1981) and synchronous changes are apparent in its optical light curve (Chevalier et al., 1981). The optical component of SMC X-1, Sk 160, is a B 0.5 Ia supergiant, that of LMC X-4 is an O 8 III-V type star (Bradt et al., 1979).

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* Based on observations by the International Ultraviolet Explorer collected at the Villafranca Satellite Tracking Station of the European Space Agency

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We have made systematic IUE low-resolution spectroscopic observations of these two sources in an effort to understand the effects of the X-rays on the stellar winds of the primaries and to study the ultraviolet light variations of the optical stars.

A first general description of the ultraviolet spectra of LMC X-4 and SMC X-1 was given by Tarenghi et al. (1981). However, these authors had only one spectrum available and thus could not discuss any binary phase UV variations. Most of the data reported here were taken in August 1979 and April 1980. A brief preliminary presentation of the data obtained in 1979 in the 1200-2000 Å wavelength region has been given in Bonnet-Bidaud et al. (1980). A more detailed discussion of the 1979 data, including continuum model-atmosphere fits and light curves can be found in a second paper (Bonnet-Bidaud et al., 1981; herein after referred to as Paper I).

II. The Observations

Ultraviolet spectra of LMC X-4 and SMC X-1 were taken with the IUE satellite at the ESA Villafranca Station during the periods 16-19 August 1979 and 5-8 April 1980 in the low-dispersion mode (6 Å resolution) and in the two wavelength ranges 1200-1950 Å (SWP) and 1900-3200 Å (LWR). The exposures were made using the large entrance aperture (10" × 20") with integration times of typically 30 and 45 minutes for SMC X-1 and LMC X-4, respectively. We have also included in our analysis several low-resolution spectra taken earlier by ESA and NASA observers. In all there are 16 SWP spectra and 12 LWR spectra for LMC X-4 and 13 SWP spectra and 10 LWR spectra for SMC X-1. Details for the 1980 spectra are given in Table 1 and for the earlier spectra in Paper I.

All SWP spectra were reduced in a homogeneous way, using the computer code by Snijders (1980) who also provided an appropriate calibration curve.

III. The Results

3.1. The continuum

We have fitted model-atmosphere fluxes (Kurucz, 1979) to the 1979 and 1980 data separately and to the average of all spectra for each source in a manner similar to that discussed in Paper I. In Table 2 we give the best fit parameters for the temperature and the gravity for reddening values derived in Paper I. We see that for SMC X-1 there is no difference between the three averages, whereas for LMC X-4 there is a weak evidence for a difference in temperatures for 1979 and 1980. This difference is marginal however, and may not be really

Table 1. List of IUE spectra of LMC X-4 and SMC X-1 obtained in April 1980

Date	Obs	Phase*	SWP	t_{exp} (min)	Phase*	LWR	t_{exp} (min)
LMC X-4							
5.04.80	ESA	0.49	8663	45	0.52	7417	45
5.04.80	ESA	0.54	8664	45	0.57	7418	45
6.04.80	ESA	0.27	8674	45	0.29	7427	45
6.04.80	ESA	0.32	8675	45	-	-	-
7.04.80	SRC	0.90	8686	45	0.87	7436	45
7.04.80	SRC	0.99	8688	45	0.01	7438	30
7.04.80	SRC	0.03	8689	41	-	-	-
SMC X-1							
5.04.80	ESA	0.85	8662	37	0.86	7416	25
6.04.80	ESA	0.13	8673	37	0.14	7426	25
7.04.80	SRC	0.40	8687	37	0.39	7437	25
8.04.80	ESA	0.62	8701	37	0.63	7448	25

*phase zero = JD 2443116.9443 + n × 3.892387 (SMC X-1) (Bonnet-Bidaud and van der Klis, 1981)
JD 2443476.40 + n × 1.40830 (LMC X-4) (Hutchings et al., 1978)

significant. The average values for the temperature are slightly different from those reported in Paper I, but within the uncertainties given in that paper. The values for the T_{eff} obtained from the IUE spectra are a bit cooler than those derived from the optical data alone (see Paper I). This fact needs to be investigated further.

3.2. Light curves

We have studied the phase variability of the ultraviolet flux from both sources in 8 different broad-band (100 to 250 Å) wavelength regions between 1300 Å and 3100 Å and compared these data to calculated theoretical light curves for a tidally distorted early-type star, heated on one side by X-rays. Our light curve synthesis programme has been described in Zuiderwijk et al. (1977). The ellipsoidal light variations are calculated according to the geometry of the system (assuming corotation), using von Zeipel's theorem and a grid of model-atmospheres given by Kurucz (1979) to determine the flux emerging from each point of the stellar surface. The heating by X-rays is taken into account by the simple "deep heating" approximation (see van Paradijs and Zuiderwijk, 1977).

a. LMC X-4

Fig. 1 shows the observed ultraviolet flux variability, obtained by folding the normalization constants from the model-atmosphere fits. The eight individual broad-band regions give essentially the same results and the calculated light curves indicate only a marginal wavelength dependence ($<0\overset{m}{.}015$) of the amplitudes between 1300 Å and 3100 Å. It is immediately clear that the observed light curve in April 1980 differs strongly from the one of August 1979 around binary phase 0.5, where we see the X-ray source in front of the optical star. For the theoretical light curves (full lines) we used system parameters as found in Chevalier and Ilovaisky (1977) and Hutchings et al. (1978); these are specified in the figure caption. The curves were normalized to the flux measured at phase zero, where the unheated side of the primary is visible. The deep minimum observed in 1979 cannot be explained by an ellipsoidal light variation alone. The light curve observed in 1980

Table 2. Results of model-atmosphere fits to the ultraviolet spectra of LMC X-4 and SMC X-1

	log g	T_{eff} 1979	T_{eff} 1980	T_{eff} average
LMC X-4 E_{B-V}=0.05	4.0	27750 ± 1900 (2σ)	25500 ± 1900	27250 ± 2250
SMC X-1 E_{B-V}=0.08	3.0	24000 ± 1400	23500 ± 1700	24000 ± 1400

could be explained by an X-ray heated primary atmosphere with $L_x \sim 1.2 \times 10^{38}$ erg/s.

After we finished this analysis, a 30.5 day variation in X-ray luminosity was discovered by Lang et al. (1981). This periodicity was detected in X-ray observations covering a period of 1½ years and remained present at the same level during this time interval. Our 1979 UV data are centered at phase 0.1 of the 30.5 day period (see Lang et al., 1981) just after the X-ray turn-on, whereas our 1980 data are centered at phase

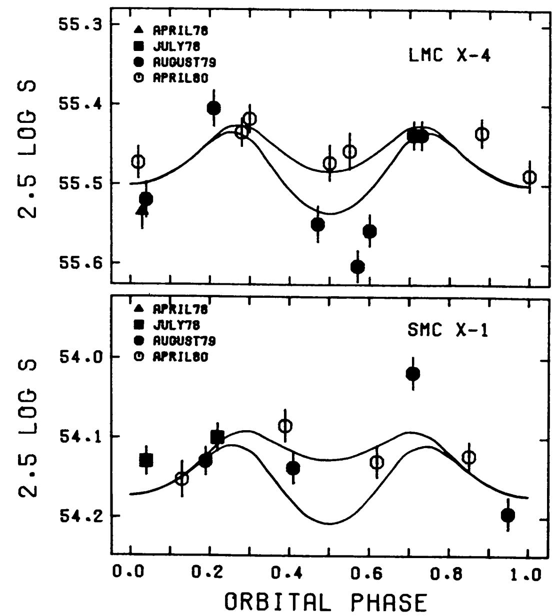

Fig. 1. Ultraviolet light curves of LMC X-4 and SMC X-1. Points shown are the normalization constants of the best fits of individual spectra to model-atmospheres. Data are plotted as magnitudes with 2σ error bars. The continuous lines represent the calculated light curves.
a) LMC X-4: light curves are calculated for $q = M_x/M_{opt} = 0.07$, $i = 75^o$, $a = 1.05 \times 10^{12}$cm, $L_{opt} = 5 \times 10^{38}$erg/s, $L_x = 0$ (deepest at phase 0.5) and 1.2×10^{38}erg/s.
b) SMC X-1: light curves are calculated for $q = 0.063$, $i = 68^o$, $a = 1.85 \times 10^{12}$cm, $L_{opt} = 8.8 \times 10^{38}$erg/s, $L_x = 0$ (deepest at phase 0.5) and 3×10^{38}erg/s.

0.75 (= X-ray low state). From a detailed analysis of the optical data (Chevalier et al., 1981) we know that during the X-ray low state we see an optical light curve consistent with ellipsoidal light variations of the primary at a constant level of heating. Our calculated light curve with $L_X = 1.2 \times 10^{38}$ erg/s fits very well to the observed B-magnitude light curve at the X-ray low state (see Chevalier et al., 1981). In Sect. IV we discuss the correlation between the X-ray intensity and the UV light curve.

b. SMC X-1

The observed ultraviolet light curve of SMC X-1 (see Fig. 1) was compared with theoretical light curves for different X-ray heating parameters. The system parameters used are the same as those used by van Paradijs and Zuiderwijk (1977). The X-ray luminosity values are consistent with the observed values (Bradt et al., 1979). The observed optical deep minimum at binary phase 0.5 is consistent with the existence of an accretion disk (van Paradijs and Zuiderwijk, 1977). However, our data do not have sufficient phase coverage around phase 0.5 to make a detailed analysis of the shape of the light curve in the ultraviolet.

3.3. Line variability

The average spectra for both sources show absorption line features which are very similar and typical for hot stars (cf. Tarenghi et al., 1981). Some of the lines are interstellar in origin and have been seen before in the spectra of Magellanic Cloud objects (Savage and de Boer, 1979; de Boer et al., 1980; de Boer and Savage, 1980). These lines originate in hot gas belonging to the Galaxy and to the Clouds. The equivalent widths of the strongest interstellar lines 1260 Å (S II, Si II), 1304 Å (O I, Si II) and 1335 Å (C II) are not variable with orbital phase and have values typical of those seen in the LMC supergiants R144 and R136 (de Boer et al., 1980). The absorption lines due to the resonance doublets N V (1240 Å), Si IV (1394-1403 Å) and C IV (1551 Å), which are predominantly formed in circumstellar matter, exhibit large variations in equivalent width with orbital phase. The equivalent width is maximum at binary phase zero. In Figs. 2 and 3 we have plotted average SWP spectra for both objects representative for different orbital phases in order to illustrate the spectacular changes taking place. The difference between the average spectrum around phase 0.25 and the one around phase 0.75 for LMC X-4 is due to a change in the amplitude of the variations between August 1979 ($\langle\phi\rangle = .75$) and April 1980 (most points of $\langle\phi\rangle = .25$), possibly related to the 30.5 day periodicity, see below. In Table 3, we give for both sources the measured equivalent widths of N V, Si IV and C IV, together with that of the interstellar C II line; percent variations around the mean value are plotted against orbital phase in Fig. 4.

The typical absolute error on equivalent width measurements is of the order of ±0.5 Å (mainly due to uncertainties in the continuum evaluation) and uncertainties on the relative variations can be assessed from the fluctuations of the C II line (± 10%), except for the N V line in SMC X-1 where the absolute error could be greater (∿1 Å) due to the slope of the continuum flux.

For the two sources, the resonance line equivalent widths exhibit similar variations, roughly symmetric around phase 0.5, with a maximum at $\phi = 0.0$ (X-ray eclipse) and a minimum at phase 0.5.

The N V line shows the strongest variations: we note that this line almost disappears completely around phase $\phi = 0.5$ for LMC X-4. C IV and Si IV show similar line variations at smaller amplitudes with a residual equivalent width at $\phi = 0.5$ which could be partially due to an interstellar component (de Boer and Savage, 1980; Prevot et al., 1980).

The equivalent widths at $\phi = 0$, representative of the undisturbed wind, are comparable for both sources to those found in MC objects and weaker than in the Galaxy, in accordance with the lower metallicity in the Clouds (Hutchings, 1980, 1981; Prevot et al., 1980).

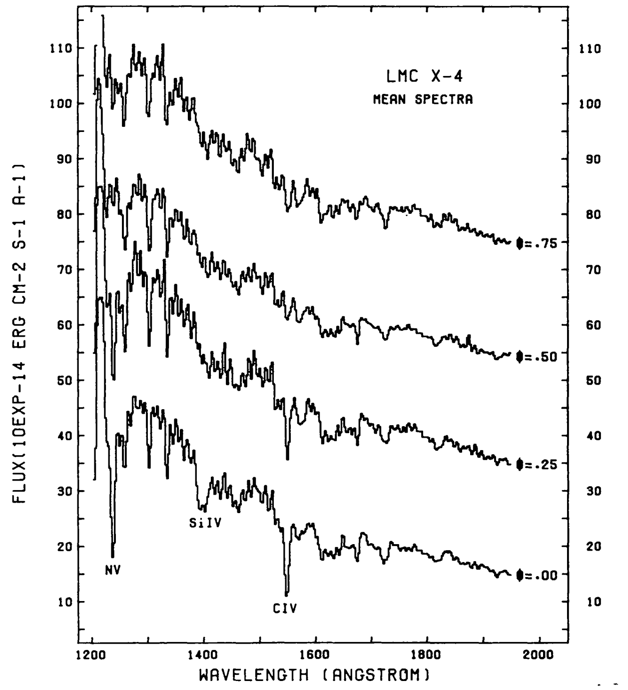

Fig. 2. Mean low-dispersion spectra of LMC X-4. Binary phases are indicated at right. Flux scale refers to $\phi = 0$ spectrum; subsequent spectra were shifted 20 flux units for clarity.

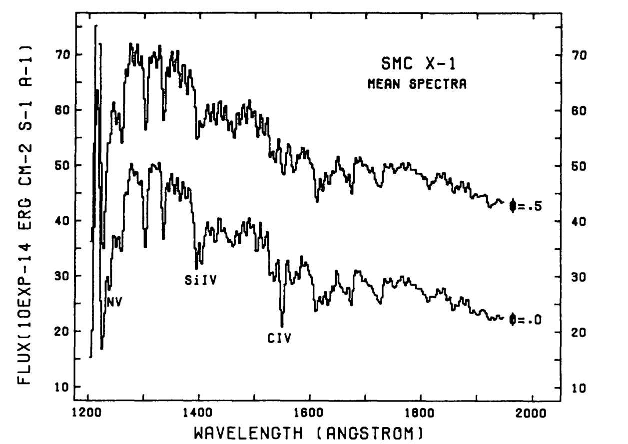

Fig. 3. Mean low-dispersion spectra of SMC X-1. Binary phases are indicated at right. $\phi = 0.5$ spectrum was shifted 20 flux units for clarity.

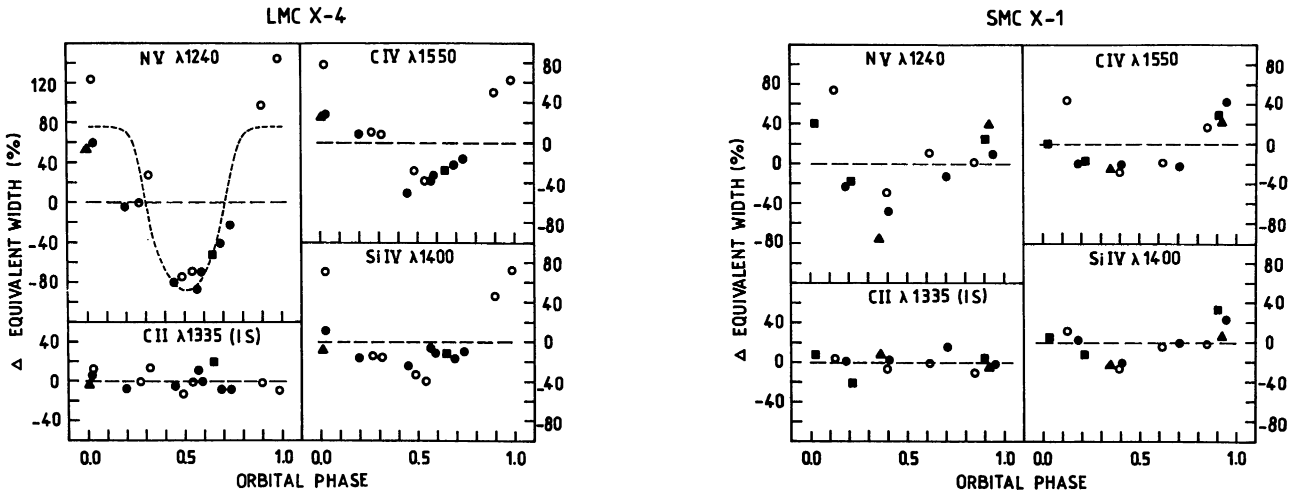

Fig. 4. Equivalent width variations for LMC X-4 and SMC X-1. The ordinate gives the deviation from the mean in percentage. Symbols are the same as in Fig. 1. The dashed curve in the N V plot (LMC X-4) represents the theoretical calculations for a coned-type surface, as described in the text and in Fig. 5.

Table 3. Equivalent widths (in Å)

SWP	ϕ	C II 1335	N V 1240	Si IV 1400	C IV 1550
		LMC X-4			
1477	0.01	1.7	4.0	4.1	5.1
6220	0.03	1.8	4.1	4.7	5.2
8689	0.03	1.9	5.8	7.3	7.2
6208	0.20	1.6	2.5	3.6	4.4
8674	0.27	1.7	2.6	3.7	3.6
8675	0.32	2.0	3.3	3.6	4.4
6202	0.45	1.7	0.5	3.3	2.0
8663	0.49	1.5	0.7	2.9	2.9
8664	0.54	1.7	0.8	2.6	2.5
6223	0.57	1.9	0.3	4.1	2.5
6204	0.59	1.7	0.8	3.8	2.7
2045	0.65	2.1	1.2	3.8	2.9
6225	0.69	1.6	1.5	3.6	3.1
6226	0.74	1.6	2.0	3.9	3.4
8686	0.90	1.7	5.1	6.3	6.1
8688	0.99	1.6	6.4	7.4	6.6
		SMC X-1			
1968	0.03	2.1	2.0	5.2	3.3
8673	0.13	2.0	2.4	5.5	4.8
6203	0.19	2.0	1.1	5.1	2.7
2020	0.22	1.5	1.2	4.4	2.7
1520	0.36	2.1	0.3	3.8	2.4
8687	0.40	1.8	1.1	3.7	2.4
6207	0.41	2.0	0.7	3.9	2.6
8701	0.62	1.9	1.5	4.7	2.7
6213	0.71	2.2	1.2	5.0	2.5
8662	0.85	1.7	1.4	4.8	3.8
2044	0.91	2.0	1.8	6.6	4.2
1533	0.93	1.9	2.0	5.2	4.0
6224	0.95	1.9	1.5	6.1	4.7

IV. Discussion and Conclusions

a. The light curves of LMC X-4

The UV light curve obtained for LMC X-4 in April 1980 is consistent with X-ray heating of the primary with $L_X \sim 1.2 \times 10^{38}$ erg/s, whereas at this time the X-ray source is expected from the 30.5 day periodicity to be in its low state. This suggests that while we are shielded from the X-rays, the primary is not, but is in fact heated by a considerable X-ray flux. Lang et al. (1981) suggest a precessing disk to explain the 30.5 d modulation. It is natural to assume that this disk is responsible for the discrepancy between observed X-ray luminosity and observed heating in our April 1980 light curve, by blocking the X-ray flux towards the earth without appreciably shadowing the primary.

During the X-ray low state, we would see the disk edge-on, but during the high state (corresponding to our August 1979 observations) it could show a considerable projected area. The anomalously deep X-ray minimum at $\phi = 0.5$ in the 1979 light curve could then be due to a partial eclipse of the primary by the disk. Similar very deep minima have also been seen in optical data (Chevalier and Ilovaisky, 1977). More recent optical work (Chevalier et al., 1981) shows, that the occurrence of these deep minima is correlated to the 30.5 day period, which supports the precessing disk hypothesis. Also the level of the two maxima of the light curve is seen to vary in these data, higher maxima being observed when the minimum is deep.

From Fig. 1 it can be seen, that at phases 0.25 and 0.75 the observed UV fluxes in August 1979 are close to those of the theoretical predictions; apparently the extra UV flux from the disk added to that of the star does not amount to more than a few hundredths of a magnitude. At phase 0.5 the partial obscuration of the primary surface by the disk makes the system fainter by $\Delta m_{0.5} \simeq 0.05$ to 0.10, depending on the amount of heating assumed. If we define α as the ratio of the projected area of the disk to the projected area of the primary, we have for small differences Δm with respect to the predicted heated ellipsoidal light curve:

$$\alpha = \frac{\Delta m_{0.5} - \Delta m_{0.25}}{2.5 \log e} = 0.92\,(\Delta m_{0.5} - \Delta m_{0.25}) \geq 0.05 \text{ to } 0.10$$

We find that for a disk with a radius equal to the mean radius of the Roche lobe of the compact object at a mass ratio $q \simeq 0.1$, the angle between the disk and the line of sight should be $\geq 25^{\circ}$ to 50° to exhibit a projected area large enough to obtain these values of α. Depending on the inclination of the LMC X-4 system ($> 70^{\circ}$, Chevalier and Ilovaisky (1977)), a disk precession angle between $12\overset{\circ}{.}5$ ($i = 77\overset{\circ}{.}5$) and 25° ($i = 90^{\circ}$) could be sufficient to allow us to see the disk changing its orientation from edge-on to the inclination angle required by its influence on the light curve. (The precession angle deduced for the disk in Her X-1 is about 30° (Gerend and Boynton, 1976).) Here limb darkening and finite disk thickness were neglected; both approximations tend to overestimate the projected disk area and thus the necessary precession angle needed to explain the observed magnitude changes.

Similarly defining τ as the ratio of the surface brightness of the disk to the surface brightness of the eclipsed part of the primary, we find:

$$\tau = \Delta m_{0.25} / (\Delta m_{0.25} - \Delta m_{0.5})$$

The uncertainty in the present measurement of the UV maxima does not allow an estimate of τ. We note, however, that the interpretation of the anomalously deep minima during the X-ray high state as due to disk obscuration implies $\tau < 1$. i.e. a surface brightness of the disk lower than that of the stellar surface in the relevant UV and optical wavelengths.

b. The line variability in LMC X-4 and SMC X-1

Orbital variations in the ultraviolet resonance lines have been observed before in two other massive X-ray binaries: Vela X-1 (Dupree et al., 1980) and Cyg X-1 (Treves et al., 1980; see also Hammerschlag-Hensberge, 1980, for a review).

Other studies of the dependence of line strengths on orbital phase in LMC X-4 were made in the optical region (Chevalier and Ilovaisky, 1977; Hutchings et al., 1978). Because these lines are formed in other regions of the stellar atmosphere than the UV lines, it is difficult to compare those results to the present ones.

The UV line variations can be understood in terms of ionisation of the companion stellar wind by the X-ray flux, and were predicted by Hatchett and McCray (HMC 1977). They introduced parametrized surfaces determined by the column density to the X-ray source, which form the boundaries between regions in which an element is ionised to a given level. These surfaces may be either closed around the X-ray source or may be open, depending on the value of a parameter 'q' which depends on the characteristics of the system (see HMC). The first type of surface has been used to interpret the variations of the P-Cygni profiles in the Vela X-1 resonance lines (Dupree et al., 1980).

Since we observe here line variations at phases as early as $\phi = 0.2$ (Fig. 4), open surfaces (corresponding to small values of 'q') seem to be more adequate. Such small values for the parameter 'q', similarly observed in Cyg X-1 for Si IV and C IV lines (Treves et al., 1980), could arise from greater X-ray luminosity and/or lower wind density than in the case of Vela X-1; this is consistent with the lack of evidence for a stellar wind in the optical spectra of LMC X-4 and SMC X-1 (Hutchings et al., 1978; Hutchings et al., 1977).

The open surfaces defined by HMC (1977) for very small values of 'q' ($q < 1$) are not strictly valid since

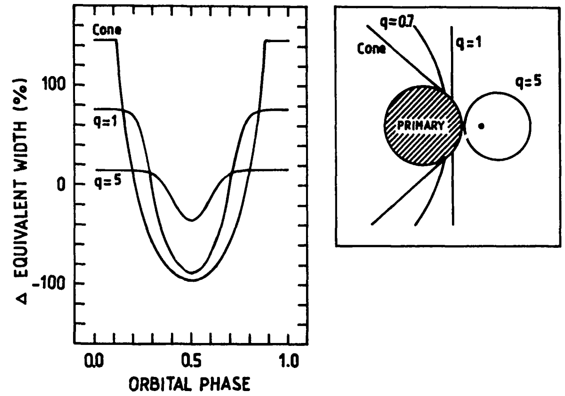

Fig. 5. Model calculations of the equivalent width variations for different surfaces (at right) in which a given ion is ionised to a higher level (see text).

they do not take into account the occultation of the X-ray flux by the primary surface. We have computed, as a function of orbital phase, the integrated column density to the projected stellar surface for a constant wind velocity law and two extreme cases of open surfaces: a plane perpendicular to the line of centers (corresponding to $q = 1$ in HMC) and a round-nosed cone with its top at the X-ray source and tangent to the primary. Those surfaces are drawn in Fig. 5, assuming an orbital separation of 1.5 stellar radii; one example of a closed surface is also given ($q = 5$). Computations for the same geometry and a non-constant velocity law (Castor et al., 1975) were also performed, but the results do not differ greatly. A coned-type surface seems to describe adequately the striking N V equivalent width variations seen in LMC X-4 (Fig. 4). For the other lines, which show a smaller amplitude for both sources, none of these surfaces can provide a good fit: the observed variations having a smaller amplitude and encompassing a larger range of phases than predicted.

We cannot, therefore, draw any conclusion on the real geometry of the ionised region for each observed ion; however, the similar variations of the Si IV and C IV lines imply comparable transparent regions for both sources, contrary to Cyg X-1 for which Si IV seems to be ionised in a more extended region than C IV (Treves et al., 1980).

The discrepancy between the observed variations and those deduced from the present discussion could be the result of the anisotropy of the X-ray flux and the variability of the X-ray illumination due to the presence of an accretion disk. In LMC X-4 in particular, such a variability seems to exist and could be related to the 30.5 days cycle, since the 1980 equivalent widths (X-ray low state) are systematically higher than in 1979 (X-ray high state) implying a reduction of the size of the transparent region.

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