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Published in:
Astronomy & Astrophysics

Astron. Astrophys. 101, 184–186 (1981)

ASTRONOMY AND ASTROPHYSICS

Ultraviolet Observations of LMC X – 4 and SMC X – 1*

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Received December 11, 1980; accepted May 7, 1981

SUMMARY

Low-resolution IUE spectra of the massive X-ray binaries LMC X-4 and SMC X-1 have been obtained at both short and long wavelengths. The continua are consistent with expected early-type model atmosphere fluxes showing small amounts of reddening and exhibit the characteristic double-wave light curves seen at visible wavelengths.

KEY WORDS

X-ray Sources - Close Binaries - Ultraviolet Spectra.

INTRODUCTION

Amongst the binary X-ray sources, the first to have been discovered in external galaxies, LMC X-4 and SMC X-1, are of particular interest due to their large X-ray-to-optical luminosity ratios (for massive binaries) and to their peculiar double-wave optical light curves (Chevalier and Ilovaisky, 1977 ; van Paradijs, 1977 ; van Paradijs and Zuiderwijk, 1978 ; see also Ilovaisky, 1980). We have made IUE low-resolution spectroscopic observations of these two sources in an effort to understand the effects of the X-ray source on its surroundings. Most of the data reported here were taken in August 1979 but we have included spectra taken in 1978 May and July. Further observations obtained in April 1980 are being analyzed and will be presented in a second paper. Here we report on the first results of our study.

OBSERVATIONS

Ultraviolet spectra of LMC X-4 and SMC X-1 were taken at the ESA Villafranca station during the period 16-19 August 1979 in the low-dispersion mode and in the two wavelength ranges : 1150-1950 Å (SWP) and 1900-3200 Å (LWR). The exposures were made using the large entrance aperture (10"x20") with integration times of 22-60 minutes. We have also included in our analysis several low-resolution spectra taken a year earlier by ESA and NASA, some of which have been discussed by Tarenghi et al.(1981). In all there are 9 SWP spectra for each source, 7 LWR spectra for LMC X-4 and 6 for SMC X-1. See Table 1 for details. A brief preliminary presentation of the SWP images has been given in Bonnet-Bidaud et al.(1980) where we discussed the striking variations in the resonance lines of CIV, NV and Si IV. Here we present results on the continuum.

Table 1 - List of IUE spectra of LMC X-4 and SMC X-1

Date	Phase	Obs	SWP	Exp.(min)	LWR	Exp.(min)
			LMC X-4			
4.05.78	0.03	ESA	1477	60	1438	60
18.07.78	0.65	NASA	2045	50	-	-
16.08.79	0.47	ESA	6202	60	5367	60
16.08.79	0.60	ESA	6204	50	5369	50
17.08.79	0.21	ESA	6208	50	5380	35
19.08.79	0.04	ESA	6220	45	5396	22
19.08.79	0.57	ESA	6223	45	5399	45
19.08.79	0.71	ESA	6225	45	5401	45
20.08.79	0.74	ESA	6226	45	-	-
			SMC X-1			
11.05.78	0.36	NASA	1520	45	-	-
13.05.78	0.93	NASA	1533	35	-	-
11.07.78	0.04	NASA	1968	40	1814	20
16.07.78	0.22	ESA	2020	35	1829	35
18.07.78	0.91	NASA	2044	32	-	-
16.08.79	0.19	ESA	6203	45	5368	35
17.08.79	0.41	ESA	6207	37	5379	28
18.08.79	0.71	ESA	6219	37	5395	25
19.08.79	0.95	ESA	6224	37	5400	25

THE CONTINUUM

Average spectra for both sources were formed using all available images. The results are shown in Fig. 1 for the combined short and long wavelength ranges with flux plotted on a logarithmic scale. We have fitted model atmosphere fluxes (Kurucz, 1979) to these data by selecting eighteen 25 Å portions of the continuum relatively free from absorption lines (see caption to Fig. 1). For LMC X-4 we explored the temperature range 25000-40000K and gravities log g = 3.5 and 4.0. For SMC X-1 we explored 20000-25000K and log g = 3.0 (see below). Visual interstellar extinction in the direction to the Magellanic Clouds is small and we explored the range in color excess E_{B-V} = 0.0 to 0.15 mag. The shape of the extinction curve in the direction to the Clouds (and in them) is not well known, but Koornneef (1980) and Nandy et al.(1979) have shown that in the 30-Dor region of the LMC the extinction curve has a smaller "bump" at 2200 Å and rises more steeply for wavelengths shorter than 1900 Å than the so-called "galactic" law (Seaton, 1979).

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

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In Table 2 we give the results of the minimum χ^2 3-parameter fits to the average spectra. For each gravity we give the derived effective temperature, color excess (assuming a ratio $A_V/E_{B-V}=3.2$ [1]) and the log of the normalization constant (in c.g.s. units) together with their 95 % confidence intervals, as well as the minimum χ^2 value and the corresponding probability of exceeding this value in a χ^2 distribution with 15 degrees of freedom.

Table 2
Best-fit Model Atmosphere Parameters
Derived from IUE spectra of LMC X-4 and SMC X-1

log g	T_{eff}	E_{B-V}	χ^2_{min}	P(>χ)	log S
		LMC X-4			
3.5	30000±6000 K	0.02±0.02	10	82%	22.327
4.0	30000±5000 K	0.05±0.02	8	92%	22.210
		SMC X-1			
3.0	25000−7500 K[1]	0.09±0.02	12	68%	21.620

[1]For log g = 3.0 no models hotter than 25000 K are given bu Kurucz (1979). This may arise from radiation pressure instabilities.

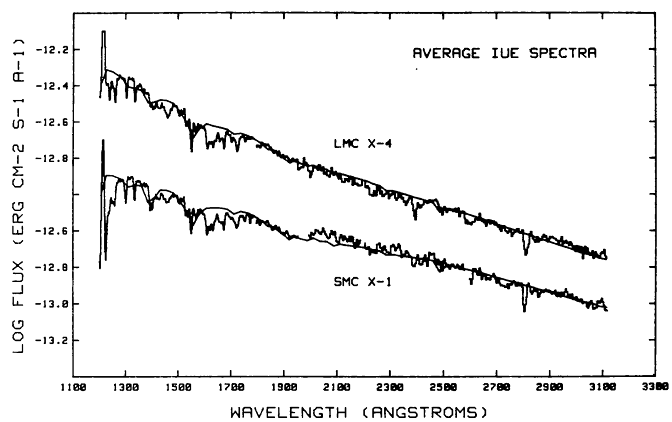

Fig. 1 Average short and long wavelength spectra of LMC X-4 and SMC X-1. Data are plotted in 2 Å bins for 1950 Å and in 4 Å bins for 1950 Å. Logarithmic flux scales are shown at left for LMC X-4 (top) and SMC X-1 (bottom). Model atmosphere fluxes shown as a continuous line are discussed in the text. For LMC X-4 T_{eff} = 30000 K, log g = 4.0 and E_{B-V} =0.05 mag, while for SMC X-1 T_{eff} = 25000 K, log g = 3.0 and E_{B-V} = 0.09 mag. The extinction law used is that of Koornneef (1980) and Nandy et al (1979). The central wavelengths for the 25 Å bands used in the fits are : 1287.5, 1362.5, 1487.5, 1587.5, 1697.5, 1767.5, 1832.5, 1897.5, 2012.5, 2150.0, 2312.5, 2460.0, 2540.0, 2662.5, 2762.5, 2862.5, 2932.5 and 3012.5 Å.

[1]Note that for the Magellanic Clouds a value of 2.65 might be more appropriate (Madore, 1977) but the effect on the fits is negligible.

In the case of LMC X-4 the best-fit model has T_{eff}=30000 K with either log g = 3.5 or 4.0. The derived color excess is in the range E_{B-V}=0.02 to 0.05 mag depending on the gravity. Both galactic and 30 Dor-type extinction laws yield the same fits, probably on account of the small amount of reddening. The fit shown in Fig. 1 is the log g = 4.0 model with a 30 Dor-type law. For SMC X-1 the best fit model has T_{eff} = 25000 K and log g = 3.0 with E_{B-V} = 0.09 mag. The fit with a galactic-type extinction law is unacceptable (minimum χ^2 is 58 for 15 d.o.f.) and a 30 Dor-type law seems indicated. Note in Fig. 1. the slight excess of flux between 2000 and 2200 Å. The region between 1900 and 2100 Å is normally dominated by Fe III absorption lines (Koornneef 1980). As discussed in the literature (Hutchings et al., 1977), Sk 160 may be deficient in metals compared to galactic supergiants and the spectral fits in this region may be difficult.

Model atmosphere fits to the individual spectra (when SWP and LWR images were taken in close sequence) show no significant temperature variability about the mean value.

Optical spectra of LMC X-4 indicate a spectral type between 07-09 with a luminosity class III-V (Chevalier and Ilovaisky, 1977 ; Hutchings et al. 1978), corresponding to a temperature range 38500-31000 K for gravities between log g = 3.5 and 4.0 (see Conti, 1973). The average U-B and B-V colors of LMC X-4 (see Chevalier et al., 1980) are consistent with Kurucz model atmospheres having T_{eff} = 34000 - 31000 K and log g = 3.5 to 4.0 with color excess in the range E_{B-V} = 0.05 to 0.06 mag. Estimates of the visual foreground extinction in the direction to the LMC have been given by Brunet (1975), Crampton (1979) and Dachs (1970) and range from E_{B-V} = 0.03 to 0.06 mag.

In the case of SMC X-1/Sk 160, the optical spectra indicate a type B0 Ia with temperatures in the range 28000-31500 K and gravities 3.1 to 3.4 (Osmer and Hiltner, 1974 ; Hutchings et al, 1977 ; see Panagia, 1973). Published U-B and B-V colors for Sk 160 (Butler and Byrne, 1973 and Penfold et al, 1975) are in agreement with Kurucz model atmospheres with T_{eff} between 24000 and 25000 K for log g = 3.0 with derived color excess between E_{B-V} = 0.07 and 0.08 mag. For the SMC, minimum values for the color excess vary between E_{B-V} = 0.04 and 0.07 mag (Azzopardi and Vigneau, 1977 ; Walborn, 1977 ; see also Prévot et al., 1980).

It is thus apparent that the temperatures and color excesses derived from the ultraviolet data agree very well with values estimated from the optical data. Moreover, the reddening observed for both sources may be foreground.

LIGHT CURVES

We have studied the phase variability of the ultraviolet flux from both sources, by folding the normalization constants in the model atmosphere fits. This procedure makes use of all the available spectral information on the continuum. As the spectra do not show any significant T variations, we have adopted a constant T in these fits. The parameters used are : T = 30000 K, log g = 4 ; T = 25000 K, log g = 3 respectively for LMC X-4 and SMC X-1.

The light curves shown in Fig. 2 are in basic agreement with those reported in Bonnet-Bidaud et al. (1980), which were based on a single wavelength band at λ1487 Å. Superposed on these data are the schematic visual light

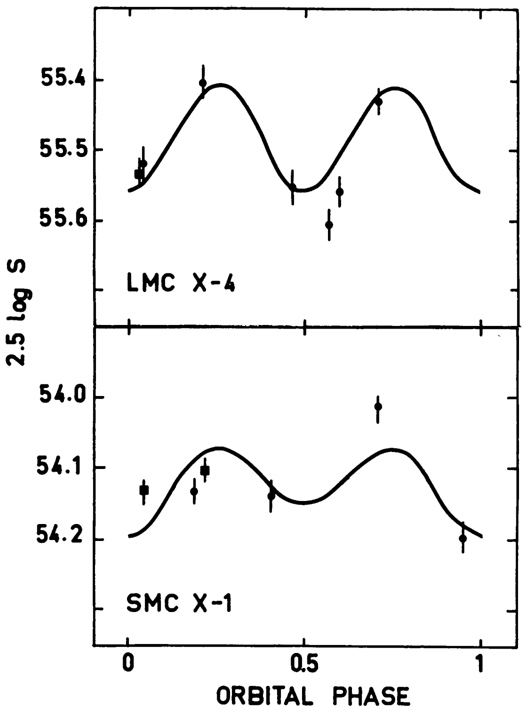

Fig. 2 Ultraviolet light curves of LMC X-4 and SMC X-1. Points shown are the normalization constants of the best fits of individual spectra (Temperatures and gravities are taken from the best average fits (see Figure 1)). Filled squares represents 1978 data and filled circles 1979 data. The continuous lines represent the schematic optical light curves taken from the literature. Data are plotted as magnitudes with $\pm$ 1 error bars.

curves taken from Chevalier and Ilovaisky (1977) for LMC X-4 and from van Paradijs (1977) for SMC X-1. These curves have been fitted to the data points by setting their mean value equal to the average of the data. The fit for LMC X-4 is rather good (with the exception of one high point at phase 0.0) but for SMC X-1 there is more scatter (as well as a very high point at phase 0.7).

CONCLUSIONS

The observed ultraviolet continua of LMC X-4 and SMC X-1 have been found consistent with theoretical fluxes from model atmospheres of effective temperature and gravity as indicated from optical spectra and colors. Reddening is small in both cases and may be essentially foreground. In the case of SMC X-1/Sk 160 the reddening law required ressembles that derived for the LMC 30 Dor region.

The continuum variations with phase we see in the ultraviolet are apparently quite similar to those seen in the visible range. These double-wave light curves have been usually explained in terms of the distorted shape of the primary. However, for LMC X-4 and in a lesser degree for SMC X-1, the amplitude is too large to be explained solely in terms of this effect and some light may be coming from the accretion disk (van Paradijs and Zuiderwijk, 1978 ; Chevalier and Ilovaisky, 1977 ; Hutchings, 1980 ; Ilovaisky, 1980). As the ultraviolet spectra reported here show no striking evidence for any wavelength depend effect, the disk must have the flux distribution typical of a hot star like the primary itself.

ACKNOWLEDGEMENTS

We thank ESA and the SRC for observing time on IUE. JMBB acknowledges a CEA fellowship and MM a DGRST fellowship. SAI is supported by the CNRS, G.H-H and MvdK are supported by the Netherlands Organisation for the Advancement of Pure Research, Z.W.O. (ASTRON). We acknowledge useful discussions with Drs. C. Chevalier and Ch. Motch.

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