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FAR UV OBSERVATIONS OF BLACK HOLE CANDIDATES: THE CASE OF LMC X-3†

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1. INTRODUCTION

Before the discovery of black holes it was argued that they should show up in the UV band (see e.g. Shvartzman, 1971). However, until recently, even after the discovery of a number of candidates, the bulk of information, on the black hole itself, or more specifically on the gas accreting onto the hole, was derived through other spectral bands. Still the contribution of UV information is important for a global understanding of the systems hosting the black hole, and it is now becoming clear that, for some of them, the UV band can be of fundamental importance for constraining models of the class.

The stellar mass black hole candidates observed in the far UV are reported in Table I. They represent all the best candidates known thus far (see e.g. McClintock, 1986, and Ilovaisky, 1987). All of them, but SS 433, which is heavily reddened, have been detected in the far UV. A0620-00, was observed with the ANS satellite during X-ray flaring. For Cyg X-1, LMC X-1, LMC X-3 the data derive from 10 years of successful IUE observations.

In this paper we first review briefly the observations of the two sources which have a massive non collapsed component, namely Cyg X-1 and LMC X-1. Then we consider A0620-00 and LMC X-3, whose visible component is much less luminous. The discussion will be focussed in particular on the latter object, because of its non-transient nature, and the important role of UV observations in clarifying the nature of the accretion disk around the hole.

2. MASSIVE X-RAY BINARIES: Cyg X-1 and LMC X-1.

In both Cyg X-1 and LMC X-3 the optical luminosity of the non collapsed component exceeds the X-ray luminosity (see Table 1). Because of their spectral type (O9.7Iab for Cyg X-1 and O7-9 III for LMC X-1), the stars should contribute the most part of the UV emission as compared to that of the disk. In fact there is no photometric evidence of a disk in either system, and if the mass transfer occurs through a wind it is even dubious whether a disk could form.

In the case of Cyg X-1, UV absorption lines in the stellar wind are a direct probe of X-ray emission, which is supposedly produced in the inner regions. In fact the ionization state of the wind is strongly influenced by the X-ray emission. The formation of a ionization cavity in the wind of the primary, which should produce an orbital modulation of resonance lines, was considered theoretically by Hatchett and McCray (1977) and observed immediately after the launch of IUE in Cyg X-1 and Vela X-1 (see Dupree et al 1978, 1980; Treves et al, 1980). Modulation of Si IV and C IV is illustrated in Fig. 1. From a detailed application of the Hatchett and McCray model, Davis and Hartman (1983) were able to constrain the inclination angle of Cyg X-1 ($36° < i < 67°$). The phenomenon of line modulation by the ionization bubble appears rather similar in Cyg X-1 and Vela X-1, independently of the fact that the collapsed object is, respectively, a black hole and a neutron star. Other relations between X-ray emission and UV spectrum have been searched for in Cyg X-1, with particular reference to the appearance of X-ray dips (Pravdo et al, 1980), but none was found. Of importance could be the observation of UV absorptions during a high state of the X-ray source, but to our knowledge this was never done.

The UV continuum of LMC X-1 is typical of a star of its spectral type. In particular from the absolute luminosity no indication of an undermassive primary is found (Cowley et al,1987). No orbital absorption line modulation, analogous to that of Cyg X-1 is observed in LMC X-1 (Bianchi and Pakull, 1985; Cowley et al, 1987). This is consistent with the non wind UV spectral lines. However some of the detected continuum variation can be induced by X-ray irradiation of the primary.

3. A0620-00

A0620-00 is an X-ray transient which at the epoch of its flaring (1975) dominated the X-ray sky, and remained active for several months. The optical counterpart was recognized because of its brightening by $\Delta B = 8$. After returning to quiescence the optical counterpart appeared as a K dwarf. A binary period $P = 7.7^h$, was determined by McClintock and Remillard (1986), together with a mass function $f(M) = 3.2\,M_\odot$, which makes the system probably

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TABLE I

Source	P_{orb} (days)	F(M) ($M_\odot$)	M_X ($M_\odot$)	F(1500) (erg cm^{-2} s−1 $Å^{-1}$)	Ref (UV)	L_{opt}/L_X
LMC X–1	4.2	0.14	4	$3\ 10^{-14}$	1,2	5
Cyg X–1	5.6	0.25	7	$1.5\ 10^{-12}$	3,4,5,6	10^2
LMC X–3	1.7	2.3	6	$4\text{-}7\ 10^{-15}$	7,8	10^{-2}
A0620-00	0.3	3.2	3	$1.6\ 10^{-13}$*	9	10^{-2}
SS 433	13	(10)	27	$< 5\ 10^{-16}$	10	$2\ 10^2$

* *flaring phase*

1) Bianchi and Pakull (1985) 2) Hutchings et al 1987
3) Dupree et al 1978 4) Treves et al 1980
5) Pravdo et al 1980 6) Davis and Hartman 1983
7) Treves et al 1987 8) Treves et al 1988b
9) Wu et al 1976 10) Benvenuti 1979

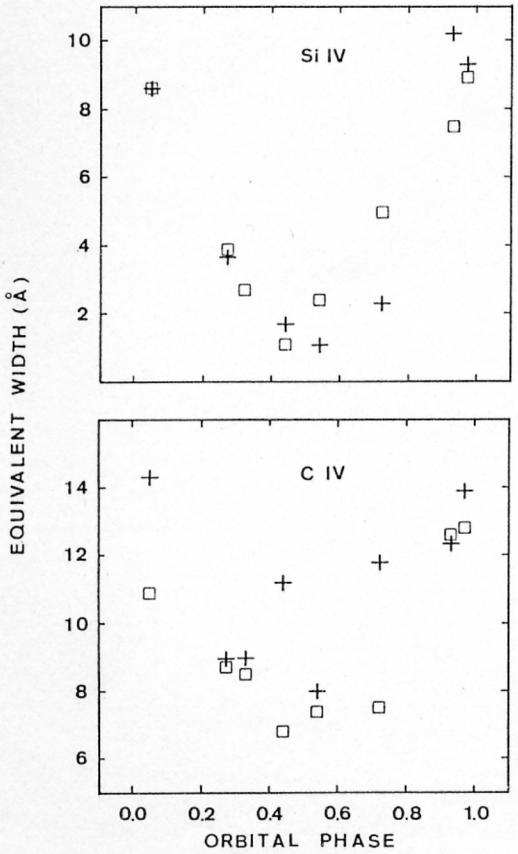

Fig. 1. Equivalent width vs orbital phase in Cyg X-1 (from Treves et al, 1980)

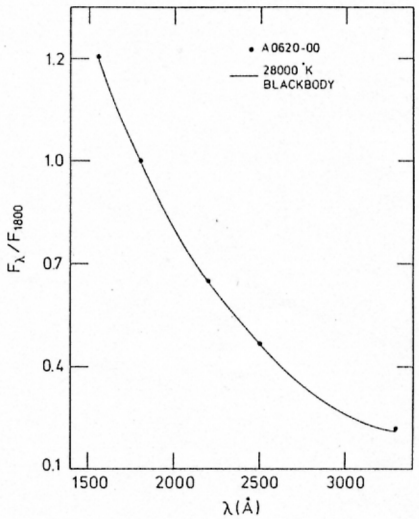

Fig.2 Dereddened UV energy distribution of A0620-00 in the flaring state; a black body distribution is fitted to the data (from Wu et al, 1976).

the clearest black hole candidate known thus far.

The 1500 to 3300 Å energy distribution was measured with the ANS satellite (Wu et al, 1976), during the explosive X-ray event. After correction for extinction, the energy distribution appears close to a black body with T = 28000 K (see Fig.2). Wu et al (1976) interpreted the UV emission as mainly due to the heating of the non collapsed component, rather than to the accretion disk. A difficulty may be the absence of a single wave light curve at maximum activity, unless the inclination angle for the system were very small.

4. LMC X-3

Evidence of the black hole nature of LMC X-3 was found by Crampton et al (1983) who measured a binary period P = 1.7^d of the B3 V optical counterpart and a mass function f(M) = 2.3 $M_\odot$. The X-ray spectrum is rather soft and the flux varies secularly by factors 100 (e.g. White and Marshall, 1984; Treves et, al 1988). In the visible it varies irregularly between V = 17.5 and 16.8. This is considered as evidence of a variable accretion disk contributing substantially to the optical emission (van der Klis et al 1983). The irregular variability is superposed to an orbital modulation of double wave shape, supposedly due to ellipsoidal modulation of the the optical component of V = 17.5 (Van Paradijs et al, 1987).

IUE observations were performed by us in 1986 and 1987 (Treves et al 1986, 1987, 1988b). At the epoch of the latter observation quasi–simultaneous optical and IR coverage was obtained (see Table 2). The IUE spectra are reported in Fig.3. A substantial variation (60%) between the two observations is apparent

The low state (1986) can be accounted for as emission of the optical star. In fact the UV data (plus V and B magnitudes corresponding to the lowest state of the source) are well fitted by a Kurucz model for a B3V star (T= 19000 K, log g = 3.7) assuming a reddening A_V^{Gal} = 0.2 and A_V^{LMC} = 0.1 (see Fig.4). The energy distribution for the 1987 high state is reported in the same figure, and is interpreted to be dominated by disk emission. In Fig.5 the Kurucz model for the low state is subtracted from the primary. The result should represent the energy distribution of the sole accretion disk. As can be noted the spectrum increases with frequency in the optical band, and decreases in the UV, indicating that the emission peaks at 3000-3500 Å. A fit with a (reddened) black body appears rather satisfactory, yielding a projected area A$\cos i$ = 3.7 10^{23} cm^2 and a temperature T = 1.4 10^4 K. From the value of A$\cos i$ an estimate of the inclination angle may follow, assuming that the disk dimension is given by the the Roche lobe of the hole. This yields i = 50° – 60° (see Treves et al, 1988b).

If substantial X-ray heating of the disk is assumed, formation of a wind or a corona above the disk is expected (e.g. Begelman et al, 1983), and the resonance lines observed in the high state UV spectrum can reasonably be generated in this region.

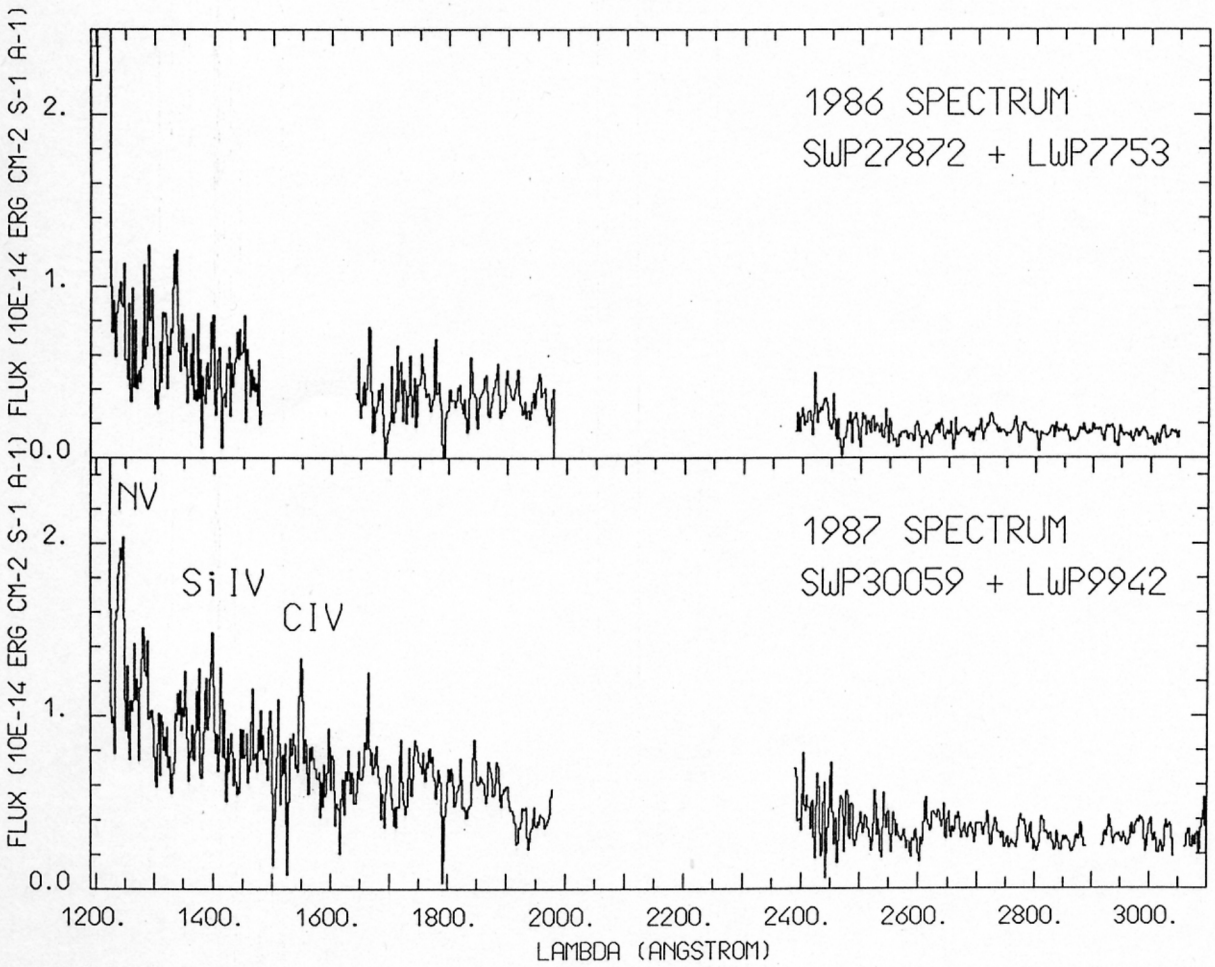

Fig. 3. IUE spectra of LMCX-3 (from Treves et al, 1988b)

Table 2

Instrument	Spectral range (Å)	Spectrum Identifier	Obs. Date	Obs. Phase	Exposure (min.)	Flux (erg cm^{-2} s^{-1} Å^{-1})
IUE	2000–3200	LWP 7753	86 Mar 7 UT 04:15	0.85	385	$F_{(2550)} = 1.6 \times 10^{-15}$
IUE	1700–1950	SWP 27872	86 Mar 8 UT 05:56	0.47	281	$F_{(1740)} = 3.94 \times 10^{-15}$
IUE	1200–1950	SWP 30059	87 Jan 9 UT 08:09	0.61	395	$F_{(1740)} = 6.50 \times 10^{-15}$
IUE	2000–3200	LWP 9942	87 Jan 16 UT 07:42	0.71	183	$F_{(2550)} = 3.37 \times 10^{-15}$
1.5m ESO BC + IDS	3850–8250	—	87 Jan 11 UT 04:00	0.69	48	$F_{(5500)} = 8.20 \times 10^{-16}$
3.6m ESO + INSb	—	—	87 Jan 8 UT 03:40	0.92	—	$J = 16.9 \pm 0.2$ $H = 17.1 \pm 0.3$ $K = 16.4 \pm 0.3$

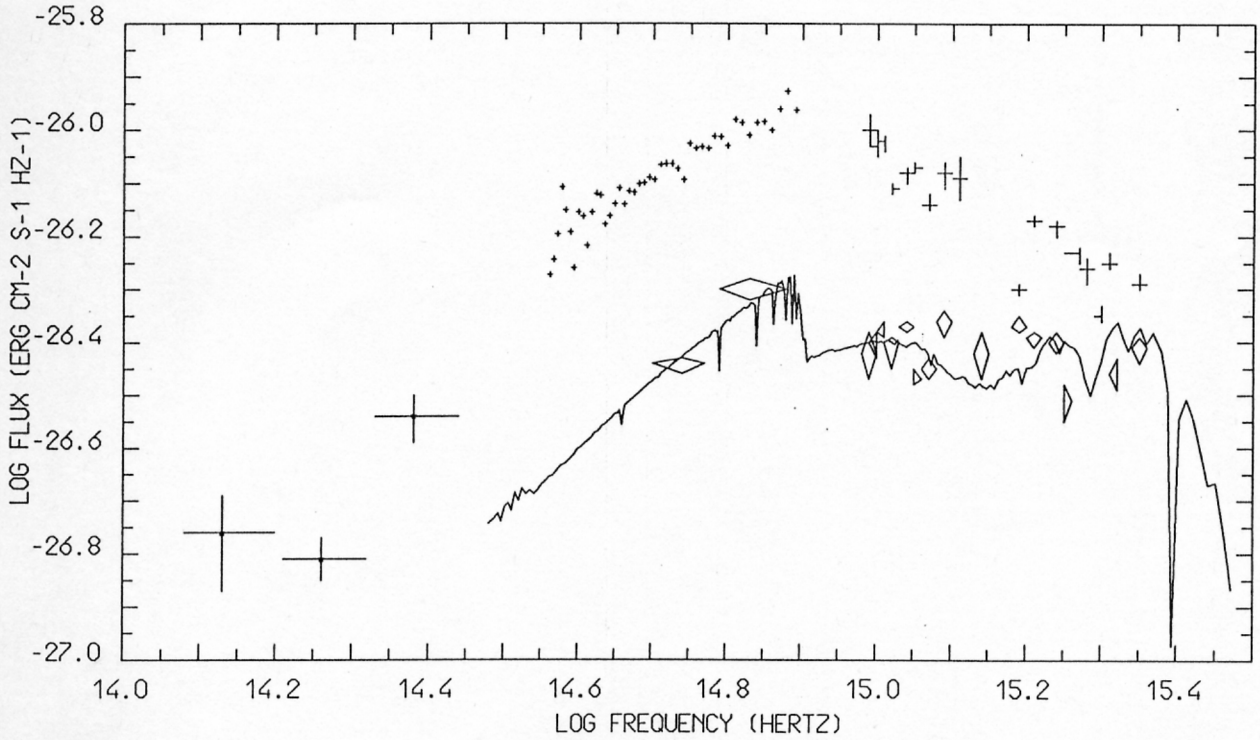

Fig. 4. Energy distribution of LMC X-3 in high and low state. The continuous curve is a reddened Kurucz's B3 V model (from Treves et al, 1988b)

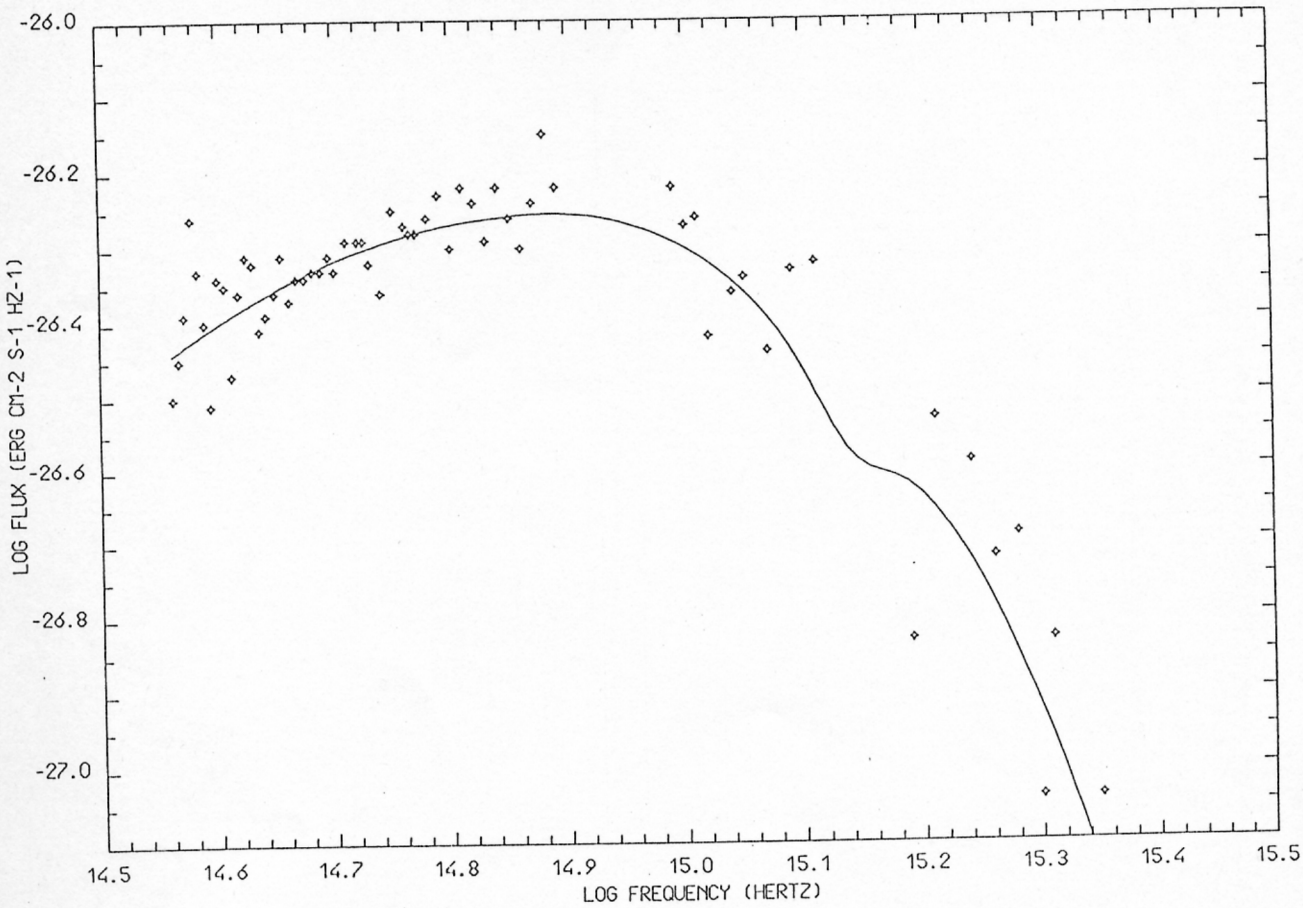

Fig. 5. Difference between high and low state energy distribution of LMC X-3. The continuous curve represents a reddened black body with T = 1.4 10^4 K (from Treves et al 1988b).

5. CONCLUSIONS

UV observations yield information on the accretion onto black hole mainly because the UV radiation is produced by the interaction of the X–rays with the accreting material. As from variability studies the dynamics of the accretion process can be reconstructed, simultaneous monitoring at UV, optical and X-ray frequencies are of the utmost importance. A collaborative program with the GINGA team is in progress for a simultaneous multifrequency study of LMC X–3.

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