THE ASTROPHYSICAL JOURNAL, 238:964–968, 1980 June 15

THE OPTICAL COUNTERPART OF THE X-RAY BURSTER SERPENS X-1 (4U 1837+04)

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Received 1979 October 18; accepted 1979 December 13

ABSTRACT

We have resolved the Davidsen candidate for Serpens X-1 into two stars separated by 2″.1. One is ultraviolet ($U - B \sim -0.5$) and shows apparent emission at He II λ4686; we identify this star with the X-ray source. Our limits on the color imply that the obscuration $A_B \leq 6.2$; this confirms that L_x/L_{opt} is very large (>100), as in such sources as Sco X-1.
Subject headings: X-rays: bursts — X-rays: sources

I. INTRODUCTION

Serpens X-1 (4U 1837+04) is an intense X-ray burst source (~250 μJy) (Doxsey *et al.* 1977; Li *et al.* 1977). A modulation collimator position from *SAS 3* (Doxsey *et al.* 1977) led Davidsen (1975) to propose an optical candidate for this source. This star was unusually blue in $U-B$ on plates taken with the Crossley 91 cm reflector at Lick Observatory. Margon, Kwitter, and Parkes (1978) investigated this candidate spectroscopically, and found an apparently normal late-type spectrum, with absorption at Hβ and Ca II H and K, and no unusual emission features. However, an extensive series of plates taken by us with the Crossley clearly resolves the Davidsen candidate into two stars separated by 2″.1. Davidsen's plates were taken in poor seeing and did not resolve the two. The fainter of the two stars in the red is by far the brighter in the ultraviolet. We proposed this as the true optical counterpart (Thorstensen, Charles, and Bowyer 1978). Subsequently Hackwell *et al.* 1979) detected an optical burst in a small diaphragm centered on this star simultaneously with an X-ray burst observed from *SAS* 3, strongly supporting our proposed identification. In this paper we discuss our extensive photographic, photoelectric, and spectroscopic observations of this star and its surrounding field.

II. OBSERVATIONS

a) Direct Imaging

Figure 1 shows enlargements of red, blue and ultraviolet Crossley plates. Inspection reveals that the southern component of Davidsen's candidate, which we label star D, is increasingly prominent toward shorter wavelengths. A more quantitative analysis is presented below.

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b) Spectroscopy

On 1978 August 6 UT we used the Lick Observatory 3 m Shane telescope and Image Tube Scanner (Robinson and Wampler 1972) to obtain separate spectra of stars DN and DS (northern and southern components, respectively) with total integration times of 56 minutes (DN) and 160 minutes (DS). We were extremely careful to avoid contributions from the unwanted star. Seeing conditions were excellent (~1″), and we used very small (1″.7 × 2″) observing apertures, with the long dimension oriented east-west. We placed the aperture north of its optimum position in obtaining the spectrum of DN, and vice versa for DS. As a consequence of these procedures, however, the effects of seeing and atmospheric dispersion render unreliable the colors and magnitudes derived from this observation, and probably cause the apparent similarity of the continuum slopes. We added to our own data on DS a short observation from 1975 September 2, provided by Dr. H. Spinrad. He resolved the two stars using the Lick acquisition TV.

Both DS and DN show Hβ absorption; emission at λ4686 is apparently present in DS, although it is not impossible that it is an artifact of the signal-to-noise ratio. The Hβ absorption is somewhat surprising in DS, as few faint blue galactic X-ray stars show it.

In addition, we obtained spectrophotometry of a number of field stars to estimate the extinction. The stars we observed are indicated in Figure 1, where numbering follows Doxsey *et al.* (1977) for all overlapping cases. Spectral types, estimated from comparison with ITS scans of stars of known spectral type, are given in Table 1. Using our photometry (described below), we calculated reddenings based on these spectral types, and distances assuming the stars are on the main sequence. These are also given in Table 1.

c) Photoelectric Photometry

We used the Kitt Peak National Observatory 2.1 m telescope and computer photometer to obtain *BVR*

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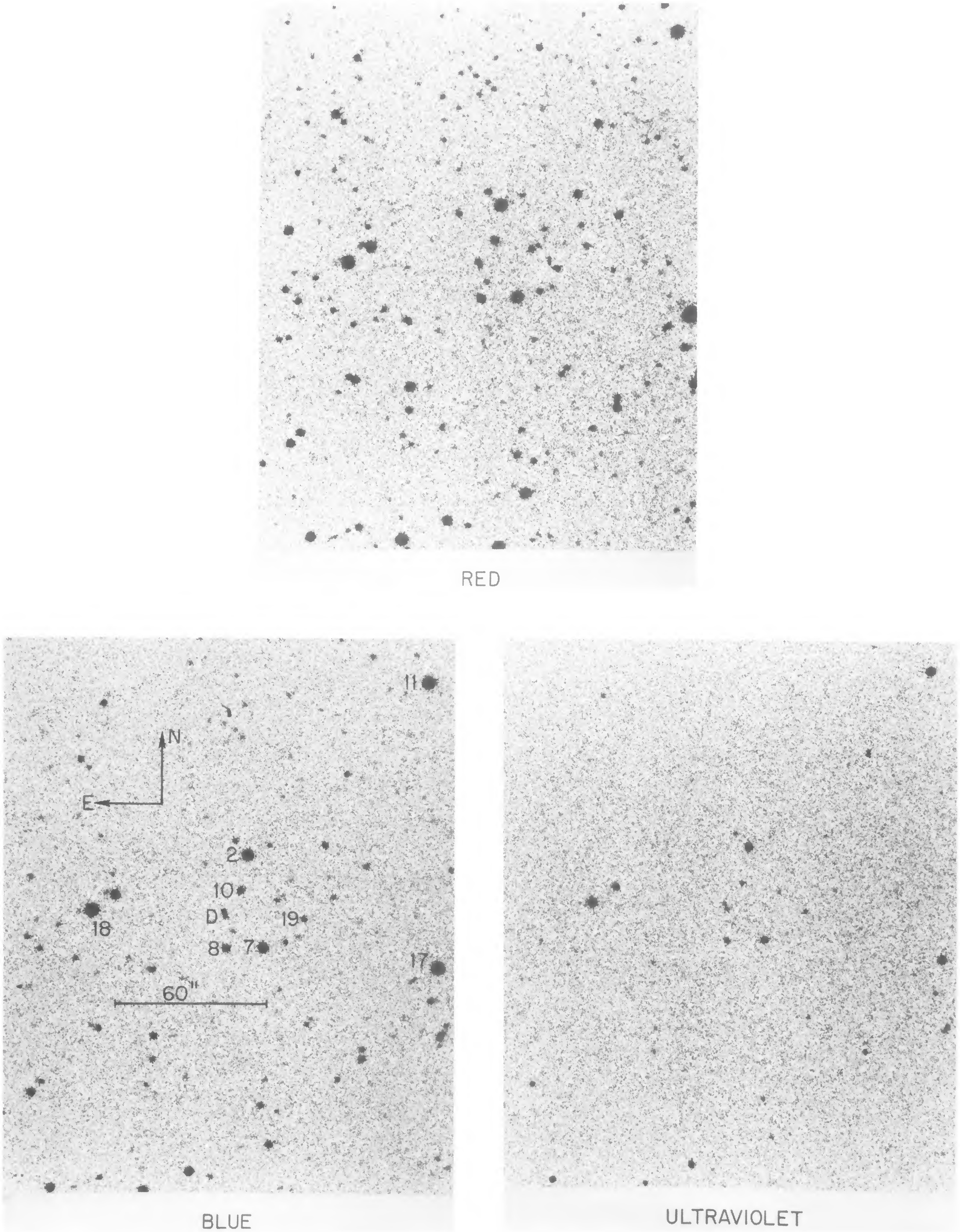

FIG. 1.—Enlargements of Crossley plates (original scale 38.″6 mm^{-1}) of the field of Ser X-1. The top panel is from a red plate (098-O2 + RG610), the bottom left from a blue plate (103a-O + GG385), and the right from an ultraviolet (103a-O + UG2) plate. Star numbers referred to in Table 1 are indicated, as is the scale and the orientation. The southern component of star D is the optical counterpart.

TABLE 1

Properties of Field Stars

Star Number	Spectral Type	V	B	U	R	d(pc)	$E(B-V)$	Notes
2	...	14.73	15.75	16.57[H]	13.92	...	...	1
7	F4–F7	15.09	16.31	16.98[H]	14.09	680	0.76 ± 0.08	
8	...	16.54[H]	17.79 (0.06)	18.40[H]	15.62	...	...	2
10	...	16.86[H]	17.94 (0.04)	18.44[H]	15.87	...	...	
11	F6–G2	14.39	15.38	15.76[H]	13.59	600	0.40 ± 0.12	
17	G0–G4	13.66	15.20	...	12.41	(160)	(0.91 ± 0.07)	3
18	F4–F8	15.15	16.01	...	...	1150	0.40 ± 0.16	4
19	...	...	18.91 (0.09)	...	16.45 (0.05)	...	...	

Note.—Magnitudes marked with a superscript H are from Hackwell *et al.* (1979). All other measures are from our Kitt Peak 2.1 m data or the Lick ITS. Statistical uncertainties are given in parentheses when they exceed 0.03 mag.

Notes.—(1) Hackwell *et al.* 1979 obtain $B = 15.93$. Taking account of possible inclusion of stars 1 and 3 in our larger diaphragm would revise our value to $B \sim 15.82$; we adopted $B = 15.8$ for photographic calibration purposes. (2) Hackwell *et al.* 1979 obtain $B = 17.59$. Because of possible transparency problems during our measurement we adopt $B = 17.65$ for photographic calibration. (3) The large implied reddening and small distance suggest that this is a giant. Luminosity class cannot be estimated from our low-resolution ITS spectra. (4) Photometry is from Lick ITS data only. Intercomparison of these data with the more accurate KPNO data shows it to be accurate to ±0.1 mag or better.

photometry of several stars in the field on 1979 July 4 and 5 UT. For several of the faintest stars, we measured only B and R. We calibrated using standards observed by Kunkel and Rydgren (1979) and Landolt (1973). We used a 10″ diameter diaphragm for all observations in this field. The results, given in Table 1, generally agree with those of Hackwell *et al.* (1979) in overlapping cases; the two significant discrepancies are noted in Table 1.

d) *Photographic Photometry*

Because of the severe crowding of the X-ray star, conventional iris methods cannot be used in photographic photometry in this field. We therefore developed a set of reduction programs for use with data from the Berkeley Astronomy Department's PDS microdensitometer. On each Crossley plate we raster-scanned over the two components of star D and 42 other stars. These stars were selected on the best blue plate; we included all stars with photoelectric measurements as well as a sampling over a range of magnitude down to the plate limit (~20 mag in blue). Before scanning each plate, we checked the centering of all the raster frames and adjusted them to within ±10 μm (0″.4) of the apparent center of the stellar image. Also, we scanned 12 rasters on blank sky to determine the background plate fog.

The reductions proceed as follows. First, the operator selects an "aperture" size over which to sum the stellar image. Apertures of 3″ to 4″ gave the most precise measures for faint ($B \sim 17$–20) stars on Crossley plates, but we used 2″ apertures in the Serpens field because of the adjacent star. The computer determines the sky fog density, b, by a straight mean over the sky frames. We then evaluate each star's brightness as follows. The density at each measured point, d_i, is compared to b and accepted if it is greater than b. Denoting these selected points by $d_{i>b}$, we take

$$M_p = -2.5 \log \left[\sum (d_{i>b} - b)^2 / n \right]^{1/2} + C ,$$

where n is the number of points so selected, C is an appropriate constant to give a rough estimate of the magnitude, and M_p is a pseudo-magnitude. The algorithm weights the denser parts of the image most heavily. Experiments on Crossley plates of M5, which has an extensive photoelectric sequence from Arp (1962), reveal that this algorithm yields fairly accurate magnitudes (± ~0.5 mag) from $B \sim 17$ to 19, even without any local calibration stars. Brighter than this range, saturation effects become important; fainter, the selection of the denser pixels gives an estimate that is too bright. If local, faint calibration stars are available, as in Ser X-1, these systematic effects may be largely removed. The rms scatter of a single measurement between $B \sim 18.5$ and 20 is typically 0.1 mag.

In the Serpens field we find no evidence for variability in the X-ray star, with a conservative limit of ±0.2 mag, on six blue (103a-O + GG385) plates taken in very good (≲1″.5) seeing. Our time resolution was typically ~30 minutes. Using Hackwell *et al.*'s ultraviolet measures of field stars for calibration, we find $U = 19.3$ (+0.3, −0.2). Using our adopted blue measures for calibration, we obtain $B = 19.15 \pm 0.2$. Our red magnitude is more uncertain, since a longer extrapolation is required from the standard stars. Based on our observed red magnitude of star D, and estimates of the magnitude difference of the pair, we find R to be in the range 17.9–18.9.

We may estimate colors for the counterpart that are considerably more accurate than the numbers above would suggest. Hackwell *et al.* (1979) give $U - B = -0.06$ for the unresolved combination of DN and DS; our plates allow us to estimate magnitude differences

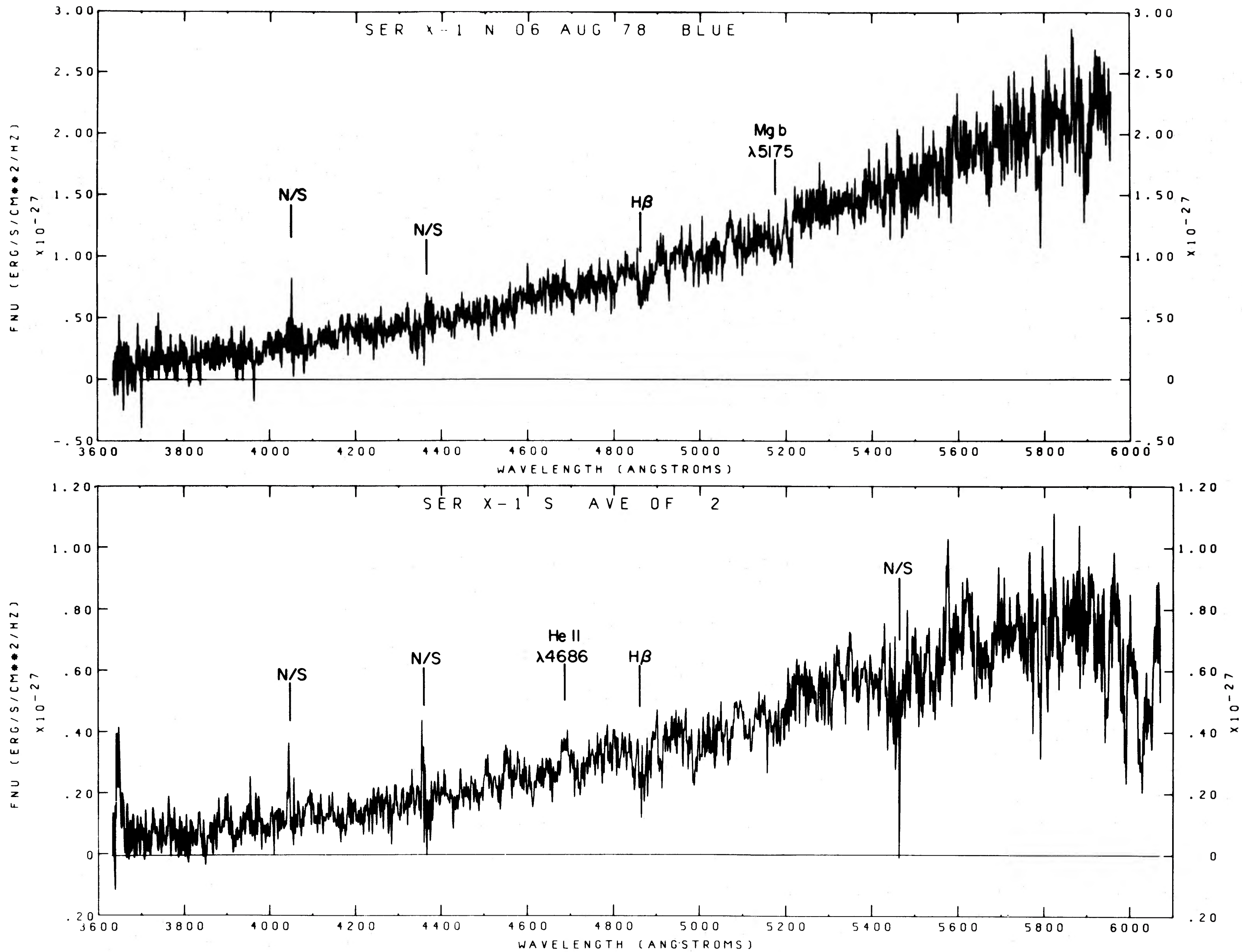

FIG. 2.—The spectra of the northern (*top*) and southern (*bottom*) components of object D, obtained with the Lick 3 m telescope and ITS. The southern component is the optical counterpart; the feature at He II λ4686 is indicated. Features marked N/S are imperfectly subtracted strong night-sky lines.

between DN and DS in both U and B. We may then solve for the colors of the two stars independently. We estimate that DS is between 0 and 0.2 mag fainter than DN in blue, and between 0.3 and 1.3 mag brighter in ultraviolet. Allowing for a ± 0.1 mag uncertainty in the quoted $U - B$ color, we find that DS has $U - B$ between -0.1 and -0.7. The reddest color we compute implies an improbably blue color ($U - B = +0.2$) for DN; the true $U - B$ color is probably nearer the blue end of the range (~ -0.5 to -0.7). Despite the uncertainty in the absolute numbers, we note that comparison of the U and B pseudo-magnitudes shows DS to be by far the most ultraviolet object we measured in this field.

III. DISCUSSION

We can estimate several interesting parameters from the available data.

a) *Reddening*

Our $U - B$ color allows us to place an upper limit on the reddening with minimal assumptions. We assume that $(U - B)_0 \geq -1.3$, the color of an infinitely hot blackbody (Allen 1973). Then $E(U - B) \leq 1.2$, and $A_B \leq 6.2$, where we have taken $R = 3.1$ and $E(U - B)/E(B - V) = 0.8$ (Allen 1973). This limit is conservative, in view of the likelihood that the star is considerably bluer (in observed color) than our limit. The field star measurements place a lower limit on the reddening, as all are at $d \lesssim 1$ kpc and Ser X-1 is almost certainly at a greater distance. However, both inspection of photographs and intercomparison of the field star measures show the obscuration in this region to be quite patchy. We take the smallest reddening we observe as a lower limit; $E(B - V) \geq 0.4$ or $A_B \geq 1.6$.

As a check, we note that Hackwell *et al.* (1979) comment that comparison of the X-ray/optical burst energies of Ser X-1 and MXB 1735 − 44 suggests an A_B for Ser X-1 about 1.5 mag greater than for MXB 1735 − 44. Since MXB 1735 − 44 likely has $0.4 \leq A_B \leq 0.8$ (McClintock, Canizares, and Backman 1978), this gives $1.9 \leq A_B \leq 2.3$ for Ser X-1, near the lower end of the allowed range.

b) *Luminosity*

Since the intrinsic optical brightness of Ser X-1 is unknown, we cannot give a photometric distance estimate. However, van Paradijs (1978) gives an estimate of 7.0 ± 0.4 kpc based on comparison with other burst sources. Our reddening limits and photometry imply that $-1.6 \leq M_B \leq +4.1$ in this distance range. The brighter limit is considerably brighter than such sources as Sco X-1 (Felten and Humphreys 1973), suggesting again that the reddening is near the low end of our allowed range.

c) *X-Ray/Optical Flux Ratio*

Our reddening estimate allows us to correct this quantity for the effects of interstellar extinction. The number given by Hackwell *et al.* (1979) for the steady X-ray to optical flux ratio becomes $130 \leq F_x/F_{\rm opt} \leq 13{,}000$; for the energies in the observed burst alone, $8.3 \times 10^2 \leq E_x/E_{\rm opt} \leq 1.2 \times 10^5$. The errors include the uncertainties both in the extinction and in the original quantities; optical fluxes are for a 1000 Å band in the blue. We conclude that $L_x/L_{\rm blue} \geq 100$, even for the largest possible reddening, and is probably at least an order of magnitude greater still.

In summary, we have shown that the optical counterpart of Ser X-1 is a faint blue star of very large $L_x/L_{\rm opt}$, similar to many other galactic X-ray stars. Our photometric results allow limits to be placed on the reddening, confirming that the large $L_x/L_{\rm opt}$ is intrinsic to the source.

Dr. I. King and D. Koo made useful suggestions for the PDS reductions. We thank Dr. H. Spinrad for use of his early Lick data and J. Stauffer for computer assistance. This work was partially supported by NSF grant AST78-06873. S. B. acknowledges the receipt of a Miller Professorship.

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