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THE DETECTION OF AN OPTICAL BURST COINCIDENT WITH AN X-RAY BURST FROM MXB 1837+05 (SER X-1)

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ABSTRACT

We report the detection of a simultaneous optical and X-ray burst from MXB 1837+05 (4U 1837+04 = Ser X-1). A similar detection was made earlier from MXB 1735−44. These are the only two burst sources that have been optically observed (simultaneous with X-ray observations) at a high level of sensitivity. Therefore, it may well be that optical bursts commonly accompany X-ray bursts. The relative timing and flux ratio of the optical and X-ray bursts imply that the optical radiation is probably re-emission from X-ray heated matter within 1–2 light-seconds of the X-ray source and no more than a few light-seconds in extent. This matter may be in an accretion disk around the X-ray source or possibly in the atmosphere of a dwarf companion.

Subject headings: photometry — X-rays: bursts

I. INTRODUCTION

The first simultaneous optical and X-ray burst was observed from MXB 1755−44 by Grindlay *et al.* (1978*a, b;* see also McClintock *et al.* 1979). Previous attempts to detect optical bursts from MXB 1837+05 have resulted in upper limits to the ratio of the optical to X-ray energy in a burst equal to $\sim 5 \times 10^{-5}$ (Abramenko *et al.* 1978; Takagishi *et al.* 1978; Bernacca *et al.* 1979).

In this *Letter* we report simultaneous optical and X-ray observations of the X-ray burst source MXB 1837+05 which have resulted in the detection of the second coincident optical/X-ray burst.

II. OPTICAL IDENTIFICATION OF THE X-RAY SOURCE

On the basis of a preliminary *SAS 3* error box (90% confidence radius $\sim 1'$; Doxsey 1975) Davidsen (1975) proposed a faint ($B \sim 18.5$) blue star as the optical candidate for Ser X-1. Confidence in this identification was strengthened when Doxsey *et al.* (1977) showed that Davidsen's star was within 4″ of the center of their improved *SAS 3* error box (90% confidence radius of 20″).

The optical spectra of the three well-established counterparts of X-ray burst sources show a blue continuum with a few superposed emission lines but no normal stellar absorption lines (see Canizares, McClintock, and Grindlay 1979, and references therein). Therefore, doubt was thrown on the identification of Ser X-1 when a spectrum by Margon, Kwitter, and Parkes (1978) showed Davidsen's object to have absorption lines similar to those expected in a late-type star. Consequently, on 1978 August 8, we made *UBV* observations of all the stars within the *SAS 3* error circle (Doxsey *et al.* 1977) using the 2.3 m telescope at the University of Wyoming Infrared Observatory (WIRO). Stars from the list by Landolt (1973) were used as calibration sources for the photometry. The results are shown in Table 1. The numbering of the stars follows Doxsey *et al.* (1977). Table 1 also includes positions of the stars relative to star 10 as determined by the encoders on the 2.3 m telescope.

The bluest object within the *SAS 3* error box is the one originally proposed by Davidsen (1975) as the optical counterpart of the X-ray source. The photometric observations thus increased our confidence in Davidsen's identification. After these observations had been made, and before we started the correlated optical/X-ray observations described in this *Letter*, Thorstensen, Charles, and Bowyer (1978) showed that Davidsen's object actually consists of two stars. The optical counterpart is a 19.2 mag blue star approximately 2″ south of the brighter (red) component. Thus, to observe the X-ray burst source, it is necessary to include a slightly brighter red star in the photometer diaphragm.

III. OPTICAL BURST MONITORING

Optical observations were made on UT 1978 September 3, 4, 6, and 7 using the 2.3 m telescope at the WIRO. The optical photometer used an EMI 9658R photomultiplier with a 2 mm thick $CuSO_4$ filter to block the tube's red response. The effective wavelength of the system is estimated to be $\langle\lambda\rangle \sim 4300$ Å with FWHM ~ 2300 Å. Diaphragms having diameters between 5″ and 15″ were used at various times during the observations, but most of the measurements were made with a 5″ diameter diaphragm. The center of the entrance aperture was positioned about 1″ south of the

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TABLE 1

PHOTOMETRY OF STARS IN FIELD OF MXB 1837+05 (Ser X-1)

Star Number[a]	$\Delta\alpha$[b] arcsec	$\Delta\delta$[b] arcsec	V	B-V	U-B
11			14.36	0.94	0.46
10	0.0	0.0	16.86	1.13	0.45
D	-7.6	-9.0	17.59	1.20	-0.06
2	+3.2	+13.6	14.76	1.17	0.64
7	+7.9	-21.7	15.13	1.21	0.64
8	-6.7	-22.5	16.54	1.05	0.81

a. Numbering according to Doxsey et al. (1977).
b. Positions relative to star #10 in arcsec.

red star so that both the signal from the red star and the one from the blue star reached the photocathode. Successive 50 ms integrations were recorded by the PDP 11/34 telescope control computer, and the results of 5 s integrations were displayed in real time. Absolute timing was maintained accurate to 10 ms by synchronizing the telescope master clock to broadcasts from WWV each evening.

Simultaneous X-ray observations were made using the *SAS 3* X-ray observatory which maintained continuous pointing to keep MXB 1837+05 centered within the 1°7 (FWHM) view of the horizontal tube detectors (Lewin *et al.* 1976; Buff *et al.* 1977). During the time that the X-ray source was occulted by the Earth as viewed from *SAS 3*, optical observations were made of standard stars and of the sky background to check instrument sensitivity and calibration.

The *SAS 3* satellite detected two X-ray bursts during the time that optical observations were being made from Wyoming. The first burst occurred on 1978 September 4 at approximately UT 03:54:00 UT. At this time, however, the source had drifted out of the 5″ diameter beam. Subsequently, the source was kept within 1″ of the beam center when a 5″ beam was being used.

The second X-ray burst observed with *SAS 3* on September 7 at 03:29:46 UT, was accompanied by a coincident optical burst (cf. Hackwell *et al.* 1979). Figure 1 shows the optical counting rate per 1 s interval and the count rates per 0.83 s interval for three X-ray channels as observed with *SAS 3* around the time of the X-ray burst. Although the peak formal deviation of the optical burst from the mean, when summed in 1 s bins, is only 3.5 σ (standard deviations), the time coincidence between the optical and X-ray bursts is striking. We are confident that the data show the detection of a simultaneous optical and X-ray burst from MXB 1837+05.

To study further the statistical significance of the September 7 optical burst, an analysis has been made of the optical data taken between UT 03:24:52 and UT 04:22:23, when uninterrupted *SAS 3* observations were made. The X-ray burster was observed for 3275 s during this period, and the remainder of the time was used to perform guiding corrections. The X-ray burst occurred approximately 240 s after these optical observations started. Figure 2 shows a histogram of the observed counting rates per 1 s for both the first 1000 s and the entire 3275 s of the observations. The 407 counts per s observed at the peak of the optical burst constitute the largest count rate (s^{-1}) observed during the first 1000 s. Only on five occasions were count rates larger than 400 s^{-1} observed during the entire 3275 s of observation, including the burst. Three of these events were within 20 s of UT 03:46:00, and the last event occurred only 150 s after this time. None of these optical events corresponds to an X-ray burst. We are uncertain as to what caused these optical "bursts." In spite of the extremely small diaphragm, it is difficult to see how they can be due to seeing and guiding fluctuations.

The width of the histograms shown in Figure 2 is about 25% greater than would be expected from a Poisson distribution. Presumably, this is due to the increased noise caused by seeing fluctuations in the small 5″ diameter diaphragm. The observed tails of the histograms are also significantly above that predicted by the best-fit Gaussian distribution. If the five events per 3275 s are typical, we must expect an event similar to that interpreted as the optical burst approximately every 650 s. If we demand that such an event be within 4 s of an X-ray burst, the chance that the observed optical burst was accidentally coincident with the X-ray burst must be less than ~0.01. An analysis of similar optical data obtained during other satellite orbits also implies that events having the same significance as that which we interpret as the optical burst, occur approximately every 500 to 1000 s.

To estimate the energy in the optical burst we have added the counts above the background count rate, during a time interval of 8 s, where the burst is clearly recognizable. The background was determined from the counts observed during intervals 40 s before and 40 s after the burst. In the calibration of the counts into energy units it was assumed that the contribution of Davidsen's object (i.e., both components) to the background corresponds to $B = 18.79$ (Table 1). Furthermore, we assumed that the spectrum is flat and we used Johnson's (1966) absolute calibration of the *UBV* system. For an adopted optical bandwidth of 1000 Å we then get for the optical burst energy density, $E_{\rm opt} = (4.8 \pm 1.3) \times 10^{-13}$ ergs cm^{-2}. This error includes only

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statistical uncertainty in the total number of counts in the burst. Other systematic errors may be present, e.g., in the calibration of the wide-band photometry.

The total energy E_x in the X-ray burst was determined from the counts observed in the burst, using a calibration based on observations of the Crab Nebula. We find $E_x = (1.7 \pm 0.4) \times 10^{-7}$ ergs cm^{-2}. The quoted error includes the statistical uncertainty and also the uncertainty due to aspect correction. These results imply a ratio of optical to X-ray energy in the burst equal to $(2.8 \pm 1.2) \times 10^{-6}$, which is consistent with the upper limits $\sim 2 \times 10^{-5}$ (for a bandwidth of 1000 Å) estimated by Abramenko *et al.* (1978), Takagishi *et al.* (1978), and Bernacca *et al.* (1979).

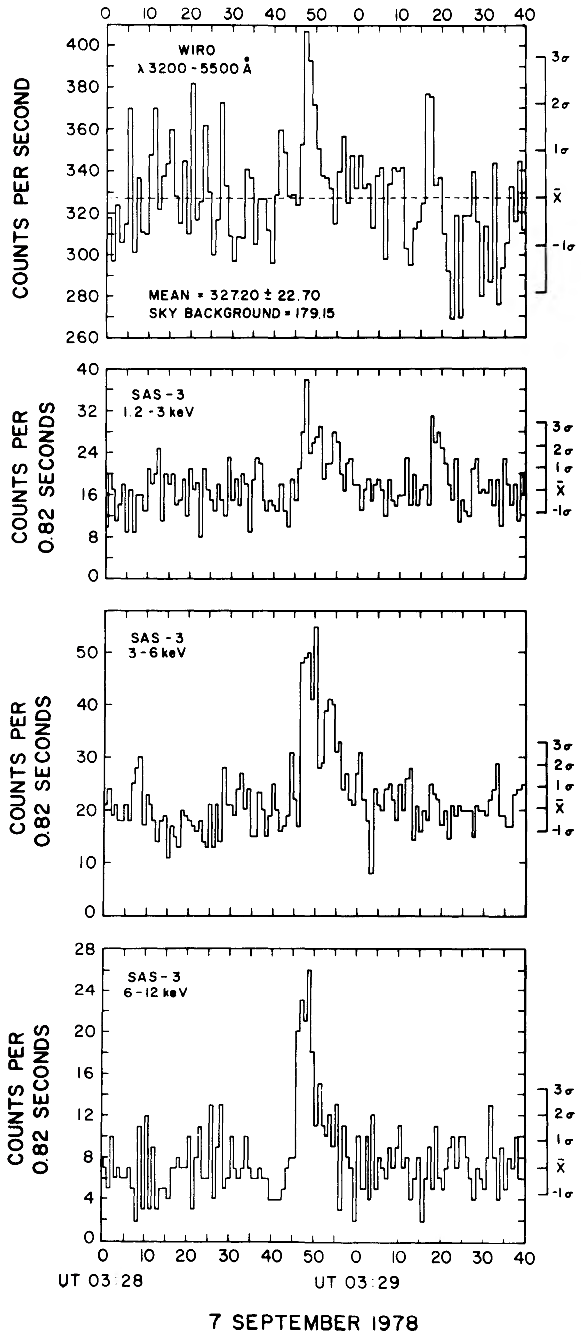

FIG. 1.—Optical (λλ3100–5400) count rate per 1 s interval as measured at the Wyoming Infrared Observatory is shown on the same time scale as the X-ray count rate per 0.83 s as measured by the three horizontal tube detectors of the *SAS 3* satellite. The optical event at 03:28:47 UT is seen to coincide closely with an X-ray burst observed by the satellite. The mean and standard deviation of the count rates are shown at the right of the figure.

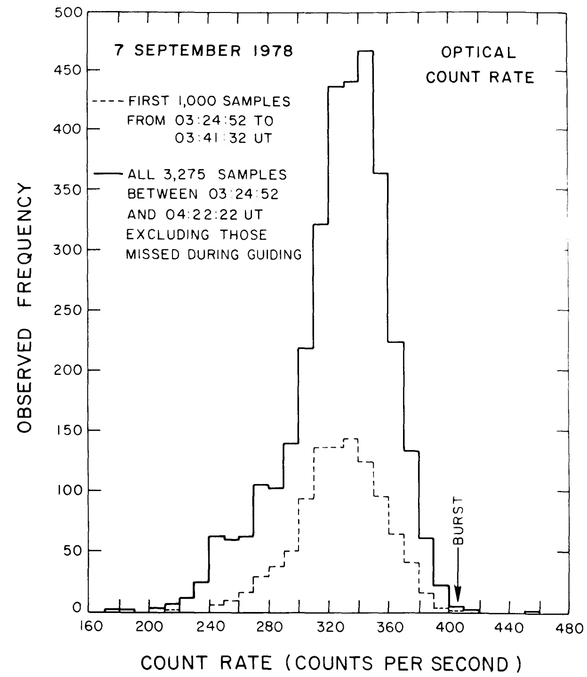

FIG. 2.—Histogram of the frequency of observed counts in the optical channel, 1978 September 7, during the period that the X-ray burst occurred.

The time difference between the X-ray and the optical bursts has been determined according to the calculations described by McClintock *et al.* (1979). We define the time of the start of the X-ray burst by the time of the first bin with a signal $>3\ \sigma$ above the background value.

From the *SAS 3* production data we find that the X-ray burst detections in the 3–6 keV channel (bins equal to 0.42 s) and the 6–12 keV channel (bins of 0.83 s) occur at UT 03:28:45.6 ± 0.2 and 03:28:45.6 ± 0.4, respectively. (These two channels contain the clearest onset of the burst signal; the bursts in the 1–3 and 8–19 keV channels seem to be somewhat delayed if we take the formal 3 σ criterion).

The optical burst starts at UT 03:28:47.0 ± 0.3, as determined from the 500 ms sampling of the counts. The errors in these times have been estimated from the bin widths of the sampling. The optical burst is thus delayed by 1.4 ± 0.5 s.

IV. DISCUSSION

Simultaneous optical and X-ray bursts have now been detected from MXB 1735−44 (Grindlay *et al.*

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TABLE 2

X-Ray and Optical Observations of MXB 1837+05 and MXB 1735−44[a]

Parameter	MXB 1837+05	MXB 1735−44[d]	
Quiescent optical flux F_{opt}[b]	1.5±0.2(−13)[c]	6.2±0.2(−13)	ergs cm^{-2} s^{-1}
Quiescent X-ray flux F_x	6.7±0.7(−9)	4.8±0.5(−9)	ergs cm^{-2} s^{-1}
Optical burst energy density E_{opt}	4.8±1.3(−13)	1.5±0.4(−12)	ergs cm^{-2}
X-ray burst energy density E_x	1.7±0.3(−7)	7.3±1.1(−8)	ergs cm^{-2}
F_{opt}/F_x	2.2±0.4(−5)	1.3±0.1(−4)	
E_{opt}/E_x	2.8±0.9(−6)	2.0±0.6(−5)	
$(E_{\mathrm{opt}}/E_x)/(F_{\mathrm{opt}}/F_x)$	0.13±0.05	0.16±0.05	

[a] Numbers in parentheses indicate a power of 10, e.g., (−9) means 10^{-9}.

[b] Bandwidth 1000 Å.

[c] $B = 19.2$ assumed.

[d] Taken from Grindlay *et al.* 1978.

1978*a, b;* McClintock *et al.* 1979) and from MXB 1837+05. Since these are the only two-burst sources which have been observed at a high level of sensitivity, it appears possible that X-ray bursts of type I (Hoffman, Marshall, and Lewin 1978) may be accompanied by optical bursts in most, possibly all, cases.

In Table 2 we have collected data on the observed burst energy and the persistent flux in the X-ray and optical spectral regions for MXB 1837+05 and MXB 1735−44. The optical results have been calculated for an assumed bandwidth of 1000 Å, as was done in the earlier papers on the optical burst from MXB 1735−44 (Grindlay *et al.* 1978*b*). The X-ray data are for the energy interval between 1.3 and 12 keV. The optical burst emission is $\sim 10^4$–10^5 times larger than is expected from a straightforward extrapolation of the $\sim 10^7$ K blackbody spectrum observed in the X-ray burst. It is therefore very likely that the optical burst is due to reprocessing of X-rays by material surrounding the X-ray burst source.

Calculations of the optical response of the matter to a sudden increase of the infalling X-ray intensity show that the change in optical intensity as a function of the X-ray intensity may be represented as $F_{\mathrm{opt}} \propto F_x^{\alpha}$, where α has a value between 0.25 and 1.0 (Milgrom and Salpeter 1975; Milgrom 1976*a, b;* Joss and Rappaport 1979). The value of $\alpha = 0.25$ corresponds to the case of simple blackbody heating, to temperatures sufficiently high that the optical radiation falls in the Rayleigh-Jeans tail of the Planck curve. From the optical burst of MXB 1735−44 a value of $\alpha = 0.22 \pm 0.1$ (consistent with this simple picture) was found (Grindlay *et al.* 1978).

It is difficult to derive an accurate value of α for the optical burst from MXB 1837+05 because of the unknown contribution of the nearby red star to the steady optical flux. However, a lower limit on α can be obtained from the assumption that *all* the steady optical light is due to the optical counterpart of MXB 1837+05. Then from $\log (F_{\mathrm{opt}}/F_x)_{\mathrm{max}} = \alpha \log (F_{\mathrm{opt}}/F_{\mathrm{x}})_{\mathrm{steady}}$ we derive $\alpha \geq 0.38 \pm 0.09$.

The results on the total energy in the optical and X-ray bursts presented in Table 2 are consistent with the idea that MXB 1735−44 and MXB 1837+05 are quite similar objects with respect to their intrinsic optical and X-ray behavior, but suffer from amounts of interstellar extinction differing by $\Delta A_B = 1.5$ mag. This is shown most clearly by the quantity $(E_{\mathrm{optical}}/E_x)_{\mathrm{burst}}\ (F_x/F_{\mathrm{optical}})_{\mathrm{steady}}$, which is approximately the same for the two objects (see Table 2).

The relative timing of the optical and the X-ray bursts and the rapid rise time of the optical burst imply that most of the optical emission originates from an emitting region less than about 1–2 light-seconds distant from the X-ray source, and less than 1–2 light-seconds in size.

This may be an accretion disk or the photosphere of a companion star. In the latter case a modulation of the delay time with the orbital period is to be expected unless the inclination angle of the orbit is very small. Variation of the delay time may also occur if the X-ray reprocessing occurs in an accretion disk and if this disk undergoes significant changes in its size and structure. Many correlated optical and X-ray bursts must be observed before we will be able to address ourselves to the problem of the nature and geometry of the reprocessing region.

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