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OPTICAL BURSTS FROM 4U/MXB 1636−53[1]

H. PEDERSEN,[2] J. VAN PARADIJS,[3] C. MOTCH,[2] L. COMINSKY,[4] A. LAWRENCE,[4]
W. H. G. LEWIN,[4] M. ODA,[5] T. OHASHI,[5] AND M. MATSUOKA[5]
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ABSTRACT

During the periods 1979 June–July and 1980 June–July, a total of 15 and 26 optical bursts, respectively, were detected from the X-ray burst source 4U/MXB 1636−53. Four of these bursts were detected in more than one passband simultaneously. The maximum burst fluxes $F_{\max}$ above the persistent optical flux and integrated burst fluxes E_b range in size over a factor of ~ 8. E_b and $F_{\max}$ are correlated, with an average burst duration, defined by $E_b/F_{\max}$, of 15 s with a standard deviation of 6 s. From a comparison with X-ray bursts simultaneously detected with *Hakucho*, it appears that the maximum optical and X-ray burst fluxes (including the persistent fluxes) are related according to a power law, consistent with the idea that the optical emission is the result of blackbody reprocessing of X-rays. The integrated optical and X-ray burst fluxes are approximately linearly related, which is not expected on the basis of this simple X-ray reprocessing picture. The average ratio of the observed integrated optical to X-ray burst flux equals 5×10^{-5}. Correcting for interstellar absorption, the intrinsic value of this flux ratio is between 2×10^{-4} and 10^{-3}. The integrated optical burst fluxes are correlated with the waiting time since the previous burst: there is an indication that large optical bursts come after a long waiting time. Thus one expects that also the integrated X-ray burst flux on the average increases with the waiting time, in agreement with Ohashi's observation that X-ray bursts from 4U/MXB 1636−53 which occur within less than 100 minutes after the previous burst tend to be smaller (by a factor of ~ 2) than the average burst size. One burst occurred only 5.5 minutes after the previous one. Such short burst intervals have also been observed in X-ray observations of the burst sources MXB 1743−28, XB 1608−522 and XB 1745−24 (in Terzan 5). They suggest that not all available nuclear fuel is consumed in the thermonuclear flash which gives rise to the X-ray burst.

Subject headings: X-rays: binaries — X-rays: bursts

I. INTRODUCTION

Correlated optical and X-ray bursts have been detected from the X-ray burst sources 4U/MXB 1735−44 (Grindlay *et al.* 1978; McClintock *et al.* 1979), 4U 1837+04 = MXB 1837+05 = Ser X-1 (Hackwell *et al.* 1979) and 4U/MXB 1636−53 (Pedersen *et al.* 1982).

The ratio of observed optical to X-ray integrated flux in the burst is typically $\sim 10^{-4}$, and the optical bursts are delayed by ~ 2 s to ~ 3 s.

An optical burst was detected from the transient X-ray burst source Aql X-1 (van Paradijs, Pedersen, and Lewin 1981). An optical burst has also been detected from the optical counterpart of the source 2S 1254−690, not previously known to be an X-ray burst source (Mason *et al.* 1980).

It is generally accepted that X-ray burst sources are a subset of the low-mass X-ray binaries, which consist of a neutron star, to which matter is transferred through an accretion disk from a low mass ($\lesssim 1\ M_{\odot}$) Roche-lobe filling companion star (for a review, see Lewin and Joss 1981, 1982). The X-ray bursts are the result of thermonuclear flashes in a layer freshly accreted on the surface of the neutron star (Joss 1979; Taam and Picklum 1979; Joss and Li 1980; Taam 1980, 1981; Ayasli and Joss 1982). The optical bursts almost certainly arise as the consequence of the reprocessing of a fraction of the X-ray burst energy by matter located within a few light-seconds of the neutron star. Pedersen *et al.* (1982) argue that an accretion disk around the neutron star is a plausible site for the reprocessing.

The delay of the optical burst is predominantly due to flight time differences between the directly observed X-rays and the X-rays which are first absorbed in the accretion disk and subsequently reemitted as optical photons. The X-ray bursts can be considered a probe of the geometric structure of matter in the vicinity of the neutron star. For instance, assuming that X-rays are reprocessed in an accretion disk, a quantitative analysis of the correlated optical and X-ray intensity variation can yield estimates of the size, thickness, and average blackbody temperature of the disk (Pedersen *et al.* 1982; Hayakawa 1981).

During the summer of 1979 and 1980, extensive simultaneous optical and X-ray observations were made

[1] Based on observations at the European Southern Observatory.
[2] European Southern Observatory.
[3] Astronomical Institute, University of Amsterdam.
[4] Center for Space Research, Massachusetts Institute of Technology.
[5] Institute of Space and Aeronautical Science, University of Tokyo.

of the burst source 4U/MXB 1636–53. The X-ray observations were made with the Japanese X-ray satellite *Hakucho* (Kondo *et al.* 1981; Ohashi *et al.* 1982). The optical observations were made using the 1.5 m Danish telescope and the ESO 3.6 m telescope at the European Southern Observatory. Burst events detected during the 1979 run in both the X-rays and in optical wavelengths have been discussed by Pedersen *et al.* (1982).

Since X-ray coverage was about 5 hr per day (because of Earth occultation, background problems in the South Atlantic Anomaly, and data telemetry constraints), many optical bursts were detected for which no X-ray data are available.

In this paper we present the results of our observations of all optical bursts detected in a "white-light" passband (see below) during the 1979 and 1980 observations. Optical bursts detected in more than one passband simultaneously will be discussed in a separate paper (Lawrence *et al.* 1982). An extensive discussion of the properties of the X-ray bursts observed during the same period from 4U/MXB 1636–53 has been given by Ohashi (1981) and Ohashi *et al.* (1982). X-ray burst properties of this source are also discussed by Hoffman, Lewin, and Doty (1977).

II. OBSERVATIONS

Time series photometry of 4U/MXB 1636–53 was carried out at La Silla during several periods in 1979 and 1980. Most of the observations were made with the Danish 1.5 m telescope, but some data were obtained with the ESO 3.6 m telescope during two nights in 1980 June. Details of the observational set ups are given in Table 1.

The observational procedure varied somewhat during the observations at the Danish 1.5 m telescope, mainly due to the changes in the construction of the photometer, described below, and due to improvements in the telescope computer control program.

The faintness of the optical counterpart of 4U/MXB 1636–53 ($V = 17.5$; McClintock *et al.* 1977) and the uncertainty about the strength of possible optical bursts from this source made the use of a very light-efficient photometer desirable. To achieve this, an existing single-channel photometer was modified in 1979 to hold a thermoelectric cold box. An antireflection-coated Barlow lens was also introduced to convert the telescope beam from f/8.6 to f/15. The cold box was used without an entrance window. Before the 1980 observations, the same instrument was further changed to carry one more photomultiplier in a thermoelectric cold box. This photomultiplier was fed by a small 90° prism placed on an X-Y table a few millimeters above the focal plane. In this way any star or sky position near the optical axis could be monitored for variations in the transparency, a facility which proved to be extremely useful.

During the 1979 observations guiding was done by optimization of the signal and tracking rate combined with occasional checks of the telescope pointing using a large field mirror. During the 1980 observations, an autoguiding system was used exclusively, thus keeping the star centered to 1″ or better.

To monitor possible variations in the sky emission and atmospheric transparency during the 1980 observations at the Danish 1.5 m telescope, the comparison channel was set on a star of such brightness that the ratio of stellar signal-to-sky brightness was similar to that of 4U/MXB 1636–53 in the main channel.

The photometric passband during the observations from 1979 June 18–23 was defined by the combination of photomultiplier sensitivity and a 10 mm thick liquid $CuSO_4$ filter. The effective wavelength is ~4300 Å, and the full width at half-maximum is ~1900 Å ("white-light" passband). During 1979 June 23–August 3 and 1980 June 14–July 15, the passband was defined by the photomultiplier sensitivity, corresponding to very nearly the same effective wavelength and bandwidth.

The observations with the ESO 3.6 m telescope were made using two different photometers. During the first night we used a four-channel photometer with *UBV*

TABLE 1

OBSERVATIONS

Period	Telescope	Photometer	Photomultiplier	Passband
1979 Jun 18–19.........	Dan 1.5 m	Roden single channel	RCA C 31034A	W ($CuSO_4$)[a]
1979 Jun 19–23.........	Dan 1.5 m	Roden single channel	EMI 9659	W ($CuSO_4$)[a]
1979 Jun 23–Aug 3.....	Dan 1.5 m	Roden single channel	EMI 9789 QB	W
1980 Jun 14–Jul 15.....	Dan 1.5 m	Roden double channel	EMI 9789 QB	W
1980 Jun 17–18.........	E.S.O. 3.6 m[b]	Four color[c]	RCA 8575	U, B, and V simultaneous
1980 Jun 18–19.........	E.S.O. 3.6 m[b]	Standard photometer	EMI 9658R	R and I sequential

[a] 10 mm liquid filter.
[b] Simultaneous with observations from Dan 1.5 m.
[c] Used without depolarizing Glan prism.

filters. According to laboratory measurements, the filter passbands agree to within a few percent with the standard passbands given in Allen (1973). However, to increase the efficiency, the photometer was used without the depolarizing Glan prism. This may have some effect on the observed *UBV* colors in case the optical source is polarized, but there is no reason to suspect that this should be the case. Guiding was done by optimization of the signal and telescope tracking rate. During the second night, the newly finished Standard Photometer was used. For these observations we used an *R* and *I* filter sequentially. Guiding was in this case done by viewing the surrounding star field in the reflecting entrance diaphragm wheel.

The white-light data from the Danish 1.5 m telescope have been reduced as described in Pedersen *et al.* (1982). *UBV* data from the ESO 3.6 m telescope were calibrated in terms of flux units using the procedure outlined by Hayes (1975). The photometric reference star was W485A (Oke 1974). The *R* and *I* band data were calibrated against the stars RGO 15, which according to Lub (1981) has $R = 9.7$, and star III-2009 ($I = 9.379$; Landolt 1973).

During the 1979 observations the sampling time interval was set to either 200 or 300 ms. During the readout time, no data were taken. The sampling is not exactly equidistant, since the readout time was somewhat variable. However UTC timing was kept accurate to 20 ms by oscilloscopic comparison of the computer clock strobe with the 15 MHz WWV signal. A correction for the delay of the WWV signal relative to UTC was applied during the data reduction.

During the 1980 observations UTC was measured using the atomic beam cesium standard frequency clock at La Silla (Ziebell and West 1980). Sampling intervals of 20, 25, and 50 ms were used during these observations. The number of counts and timing information were recorded on magnetic tape.

III. RESULTS

A total of 15 and 26 optical bursts were detected during the 1979 and 1980 runs, respectively. All, except one, were detected in the white-light passband. Two bursts were also (simultaneously) detected in the *U*, *B*, and *V* bands; one burst was also detected in the *R* band; and one in the *I* band. One burst was detected in the *R* band only.

The persistent counting rate was averaged over a time interval varying between ~1 and ~2 minutes before the onset of the burst. The sky background was observed after the optical signal had returned to its preburst level, except on the night of 1980 July 12, when the observations were not interrupted.

The data for bursts 17, 18, and 19 (see Table 2), which were observed during runs without sky measurements, were reduced assuming an approximately linear relation between airmass and sky brightness found on other nights. However, since the comparison channel diaphragm (20″) was larger than that used in the main channel (5″, 7″, or 10″.5), seeing fluctuations are not revealed in the comparison star signal.

The total number of counts in the optical bursts were determined over a time interval where they could be discerned (by visual inspection) above the background level. (If we had taken a fixed time interval for all bursts, long enough to cover the longest bursts, the significance of the detection of the shorter bursts would have been unnecessarily reduced).

The quoted errors are a combination of statistical uncertainties and estimated possible systematic errors in the energy calibration. Light cirrus was present during the nights of 1979 June 20/21 and July 27/28, and 1980 June 17/18 and 18/19, which may have introduced non-statistical errors of the order of 10%–20%.

We have also estimated the maximum flux F_{max} above the persistent flux of each optical burst. Because of the count rate fluctuations, the determination of the maximum count rate is somewhat ambiguous. Instead of taking the highest value sampled, we have taken an average value over a small time interval at burst maximum, as determined by visual inspection. The estimated accuracy of this maximum counting rate is typically ~5% of the total signal (including sky background). The accuracy of the maximum counting rate (after subtraction of the persistent flux) varies between ~5% for the large bursts and ~15% for the small ones. These maximum counting rates and total number of counts in a burst were converted into flux units (ergs cm^{-2} s^{-1} and ergs cm^{-2}, respectively) using the observed count rates of the standard stars (see also Pedersen *et al.* 1982).

In Table 2 we give the times of the onset of the bursts (to the nearest minute), maximum burst fluxes (above the persistent flux level), and integrated burst fluxes (above the persistent level) for the bursts observed in the white-light passband and the value of the quiescent flux level.

In order to give an impression of the variety of burst shapes and sizes we show the profiles of a selected sample of bursts in Figures 1 and 2. Clearly there is a large range in burst sizes, both in their flux maxima and their integrated fluxes. Histograms of the maximum burst fluxes (above the persistent level) and the integrated burst fluxes are shown in Figure 3. The total range in these quantities is a factor of ~9 and ~8, respectively.

In Figure 4 we have plotted the integrated burst flux versus the maximum burst flux. They are clearly correlated, with a burst duration, defined by E_b/F_{max} between ~8 and ~30 s (average value 15.3 s, with a standard deviation of 5.9 s). A similar relation has been observed for the corresponding X-ray quantities (Ohashi 1981).

IV. DISCUSSION

a) Comparison with X-Ray Data

For eight bursts good quality optical and X-ray data are available (see Ohashi 1981). We will limit ourselves here to a comparison of the integrated and maximum

TABLE 2

Burst Data

Burst	Date	UT	Burst Energy (10^{-11} ergs cm^{-2})	Maximum Burst Flux (10^{-13} ergs cm^{-2} s^{-1})	Quiescent Flux (10^{-13} ergs cm^{-2} s^{-1})	Remarks
1	1979 Jun 21	0017	... ...	...	5.5 ± 0.5	X
2	1979 Jun 21	0148	0.55 ± 0.09	5.3	4.8 0.8	X
3	1979 Jun 21	0334	>0.70 0.10	>6.3	>3.0 0.7	X[a]
4	1979 Jun 27	0535	1.84 0.17	10.8	4.1 0.3	
5	1979 Jun 28	0155	1.86 0.12	10.2	5.0 0.6	X
6	1979 Jul 22	0424	1.81 0.14	14.6	5.4 0.2	
7	1979 Jul 23	0052	1.39 0.08	8.6	5.6 0.2	
8	1979 Jul 28	0045	0.85 0.11	6.3	5.8 0.6	
9	1979 Jul 28	0116	0.92 0.12	6.0	4.3 0.2	X
10	1979 Jul 28	0239	1.09 0.25	5.5	4.9 0.5	
11	1979 Jul 29	0128	1.09 0.09	4.7	5.3 0.2	
12	1979 Jul 29	2329	0.59 0.15	2.0	5.6 0.4	[b]
13	1979 Jul 30	0029	0.94 0.25	4.0	4.5 0.3	[b]
14	1979 Aug 2	0324	1.98 0.19	9.7	4.2 0.3	
15	1979 Aug 3	0150	1.30 0.21	10.9	4.3 0.5	
16	1980 Jun 16	0304	0.99 0.07	12.0	9.4 0.3	
17	1980 Jun 16	0551	1.25 0.08	9.2	6.9 0.3	X
18	1980 Jun 18	0356	1.37 0.07	10.6	5.8 0.2	*UBV*, X
19	1980 Jun 18	0543	0.63 0.05	5.9	5.4 0.1	*UBV*, X
20	1980 Jun 19	0044	... ...	...	... ...	*R* data only
21	1980 Jun 19	0343	1.40 0.07	9.6	7.1 0.2	*R*, X
22	1980 Jun 19	0558	1.55 0.08	9.4	7.7 0.2	*I*
23	1980 Jul 6	0640	>1.00 0.10	...	... ...	X[c]
24	1980 Jul 8	0225	2.89 0.19	9.6	5.4 0.3	
25	1980 Jul 8	2350	2.52 0.08	18.5	5.0 0.1	
26	1980 Jul 9	0103	0.35 0.05	2.5	5.9 0.3	
27	1980 Jul 9	0535	2.60 0.09	10.2	4.2 0.1	
28	1980 Jul 9	0541	0.36 0.03	3.2	4.2 0.1	
29	1980 Jul 11	0511	2.67 0.09	18.8	5.3 0.2	
30	1980 Jul 11	0703	0.59 0.04	7.5	4.6 0.2	
31	1980 Jul 11	2318	0.58 0.05	7.9	6.9 0.2	
32	1980 Jul 12	0234	1.64 0.07	7.3	5.3 0.2	
33	1980 Jul 12	0511	0.80 0.04	7.1	5.4 0.2	
34	1980 Jul 12	0640	0.43 0.04	4.4	4.4 0.2	
35	1980 Jul 13	0238	1.99 0.08	15.6	3.8 0.1	
36	1980 Jul 14	0646	0.95 0.05	7.5	4.5 0.3	
37	1980 Jul 15	0036	1.35 0.08	8.4	5.8 0.2	
38	1980 Aug 10	0131	1.49 0.09	15.2	8.6 0.2	
39	1980 Aug 10	0307	1.92 0.16	15.5	7.5 0.2	
40	1980 Aug 10	0512	1.63 0.19	16.1	7.7 0.2	
41	1980 Aug 12	0434	2.29 0.16	15.3	9.5 0.5	

[a] Source drifting out of diaphragm.
[b] Poor photometric conditions; moonlight. Doubtful event.
[c] Poor photometric conditions; sky background highly uncertain.

burst fluxes as observed in the white-light passband and in X-rays.

In a separate paper (Lawrence *et al.* 1982) correlated X-ray and *UBV* data are discussed in some detail; a detailed study of the correlated brightness variation in the 1979 optical and X-ray bursts has been presented by Pedersen *et al.* (1982).

The maximum optical burst fluxes (including the persistent flux) are plotted versus the corresponding X-ray data in Figure 5. It appears that the maximum optical burst fluxes are approximately related to the maximum X-ray burst fluxes according to a power law, $F_{\rm opt, max}(:)F_{X,\rm max}{}^{\alpha}$ with $\alpha = 0.35 \pm 0.11$.

The assumption that all optical radiation from an X-ray burst source is due to blackbody reprocessing of X-rays (with blackbody temperatures between $\sim$30,000 and $\sim$60,000 K) has been quite successful in matching the correlated optical and X-ray intensity variations of burst 5 (Pedersen *et al.* 1982) and burst 18 (Lawrence *et al.* 1982). If all optical bursts would arise in the physical conditions found for these particular bursts, one would expect that the total optical flux would be related to the X-ray flux according to a power law, $F_{\rm opt}(:)F_X{}^{\alpha}$, with α given by the expression (Endal, Devinney, and Sofia 1976)

$$\alpha = \frac{h\nu}{4kT[1 - \exp(-h\nu/kT)]} . \quad (1)$$

For the effective wavelength of the "white-light"

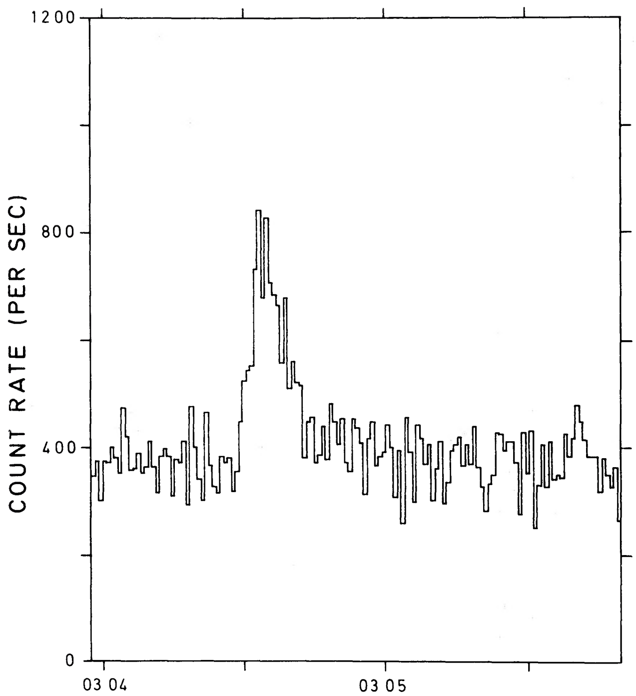

FIG. 1*a*

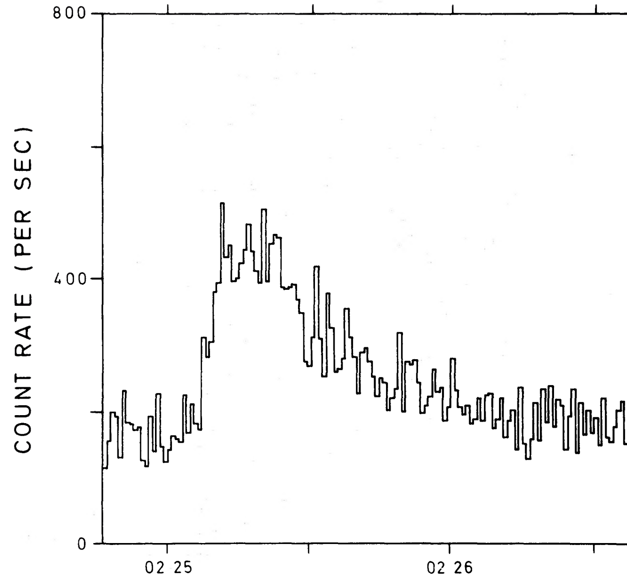

FIG. 1*b*

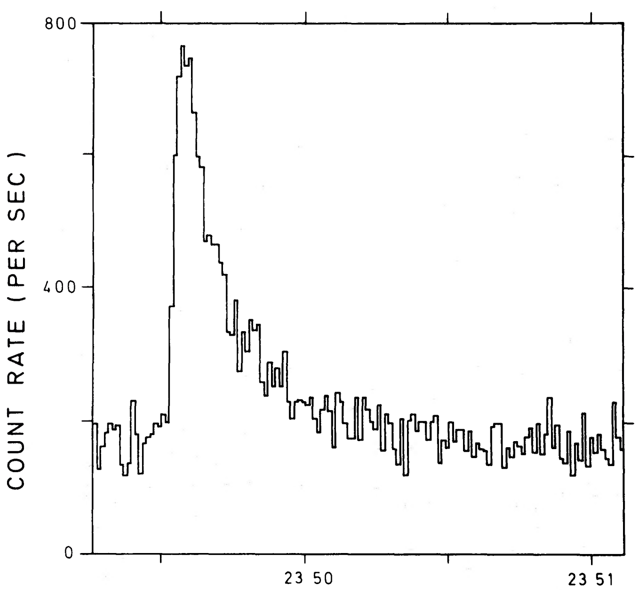

FIG. 1*c*

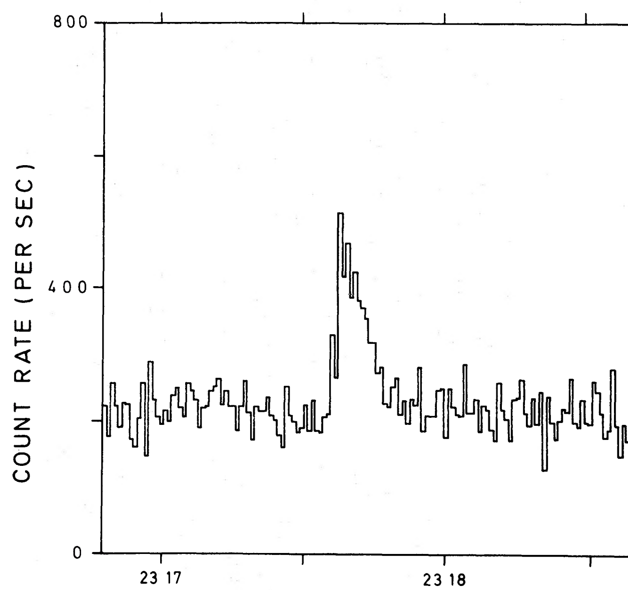

FIG. 1*d*

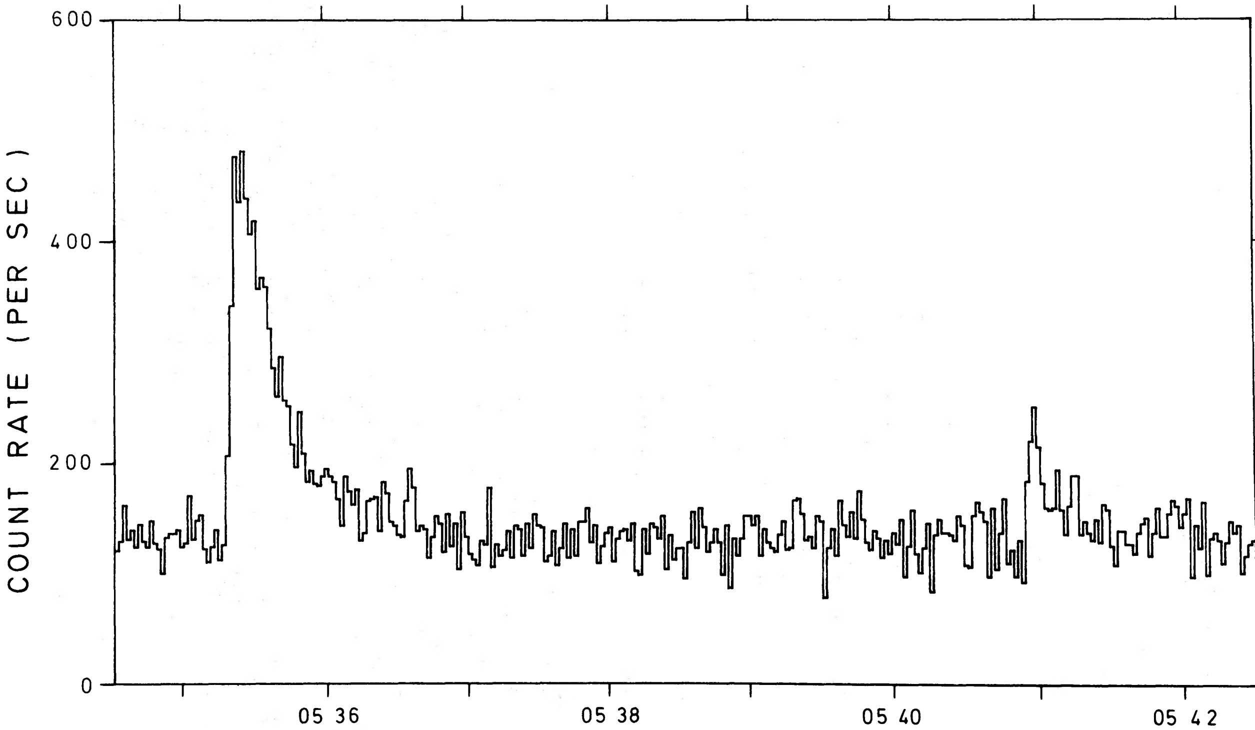

FIG. 1e

FIG. 1.—(*a*) Burst 16, as observed in the white-light passband, on 1980 June 16. The plotted signal has been corrected for sky background. (*b*) Same for burst 24, observed on 1980 July 8. (*c*) Same for burst 25, observed on 1980 July 8. (*d*) Same for burst 31, observed on 1980 July 11. (*e*) Same for bursts 27 and 28, observed on 1980 July 9.

passband used in the present observations, this expression reduces to

$$\alpha = 0.84/\{T_4[1 - \exp(-3.35/T_4)]\}, \qquad (2)$$

where T_4 equals $T/10^4$.

Using the above expression the relative decay rates of the X-ray and optical light curves of soft X-ray transients have been used to estimate the temperature (near maximum) of the reprocessing regions in these systems. The temperatures obtained for A0620−00 (Endal, Devinney, and Sofia 1976) and A1543−62 (Murdin *et al.* 1977) are near 30,000 K, in agreement with temperatures of several low-mass X-ray binaries determined from the shape of the optical and far-UV energy distributions (Wu *et al.* 1976; Hammerschlag-Hensberge, McClintock, and van Paradijs 1982).

For temperatures in the range between 30,000 and 50,000 K, the expected value of α varies from 0.42 to 0.34. The observed relation between the maximum optical and X-ray fluxes (including the persistent emission) is consistent with the above simple reprocessing picture, for temperatures near 50,000 K.

In Figure 6 we have plotted the integrated optical burst fluxes E_{opt} versus the integrated X-ray burst fluxes E_X. Because it is difficult to determine unambiguously when the optical burst has terminated and, furthermore, the persistent optical flux contributes a significant fraction to the total flux, the persistent flux level has been subtracted in these integrated burst fluxes. The observed integrated fluxes are approximately related according to $E_{opt}(:)E_X^{\beta}$, with $\beta = 1.07 \pm 0.19$. For such a linear relation, the average ratio of the observed optical to X-ray integrated burst fluxes is a meaningful quantity; its value equals 5×10^{-5}. The interstellar extinction correction appropriate to the white-light passband is in the range between a factor of ~ 4 and ~ 20 (Pedersen *et al.* 1982). Thus the intrinsic value of this ratio is between $\sim 2 \times 10^{-4}$ and $\sim 10^{-3}$.

In order to compare this result with the relation expected within the framework of the above simple X-ray reprocessing picture, we have calculated the optical response to an artificial X-ray burst which we assume to decay exponentially with an *e*-folding time τ according to

$$T^4(:)F_X(t) = F_0 + F_1 \exp(-t/\tau) \qquad (3)$$

and

$$F_{opt}(t) = B_\nu(T). \qquad (4)$$

For the persistent X-ray flux F_0, we have taken values corresponding to values of a temperature T_0 equal to 25,000 and 30,000 K (Pedersen *et al.* 1982). For the ratio F_1/F_0, which is a measure of the X-ray flux increase at burst maximum, we have taken values between 2 and 50.

The relation between the integrated optical and X-ray

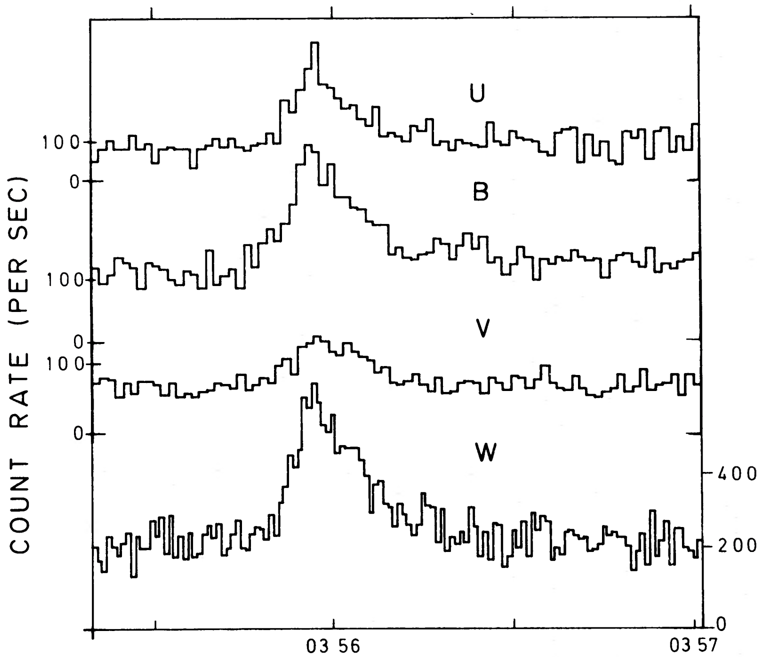
U
B
V
W
COUNT RATE (PER SEC)
100
0
100
0
100
0
400
200
0
03 56
03 57

FIG. 2*a*

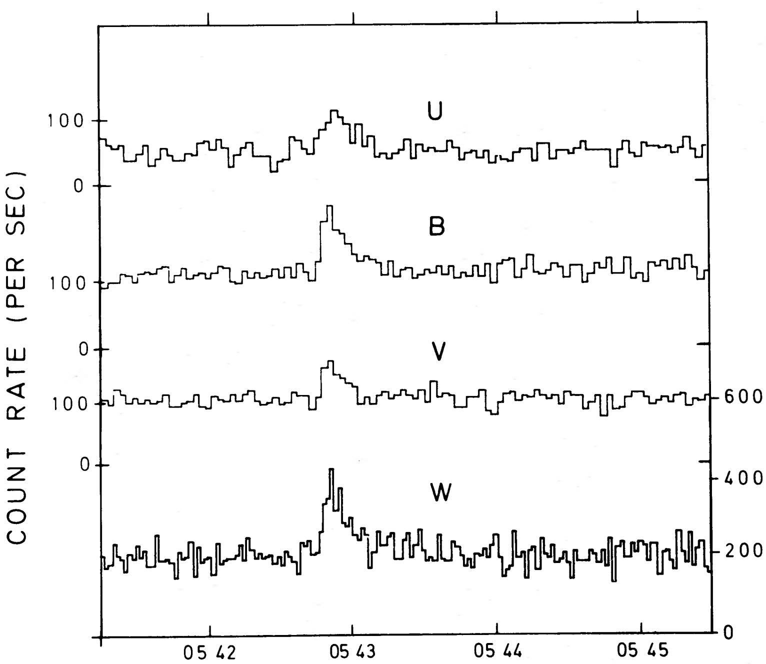
U
B
V
W
COUNT RATE (PER SEC)
100
0
100
0
100
0
600
400
200
0
05 42
05 43
05 44
05 45

FIG. 2*b*

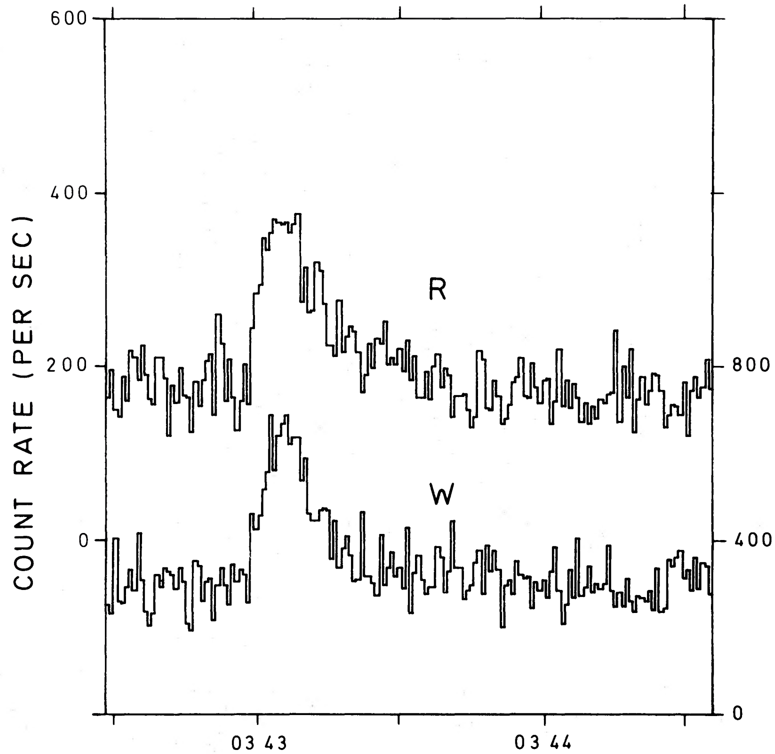

FIG. 2c

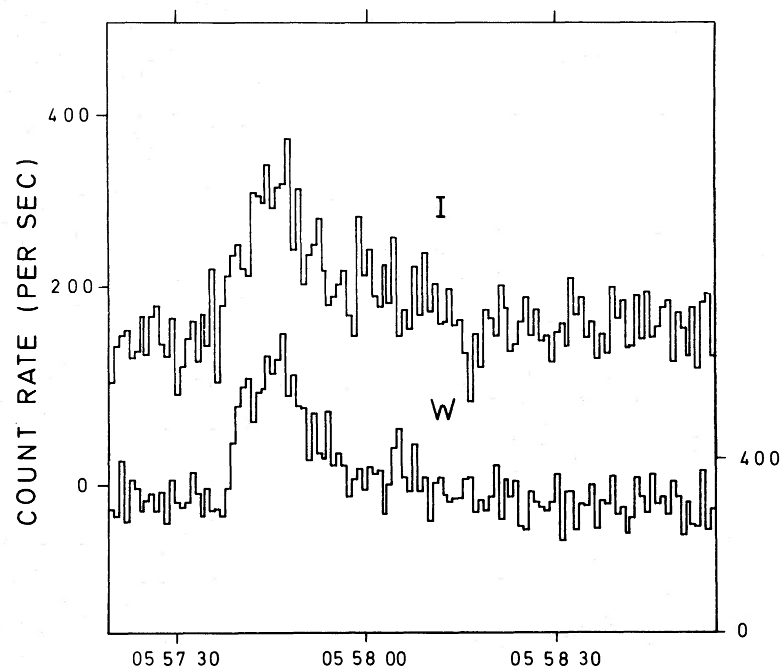

FIG. 2d

FIG. 2.—(*a*) Burst 18, as observed simultaneously in the *U*, *B*, *V*, and white light passband on 1980 June 18. The plotted signal has been corrected for sky background. The scales indicated on the left-hand side of the figure refer to the *UBV* passbands; that on the right-hand side, to the white-light data. (*b*) Same for burst 19, observed on 1980 Jun 18. (*c*) Burst 21, as observed simultaneously in the *R* and white-light passbands on 1980 June 19. The scale on the left-hand side of the figure refers to the *R* data (*top*), that on the right-hand side to the white-light data (*bottom*). The count rates have been corrected for sky background. (*d*) Burst 22, as observed simultaneously in the *I* and white-light passbands on 1980 June 19. The scale on the left-hand side of the figure refers to the *I* data (*top*); that on the right-hand side to the white-light data (*bottom*). The count rates have been corrected for sky background.

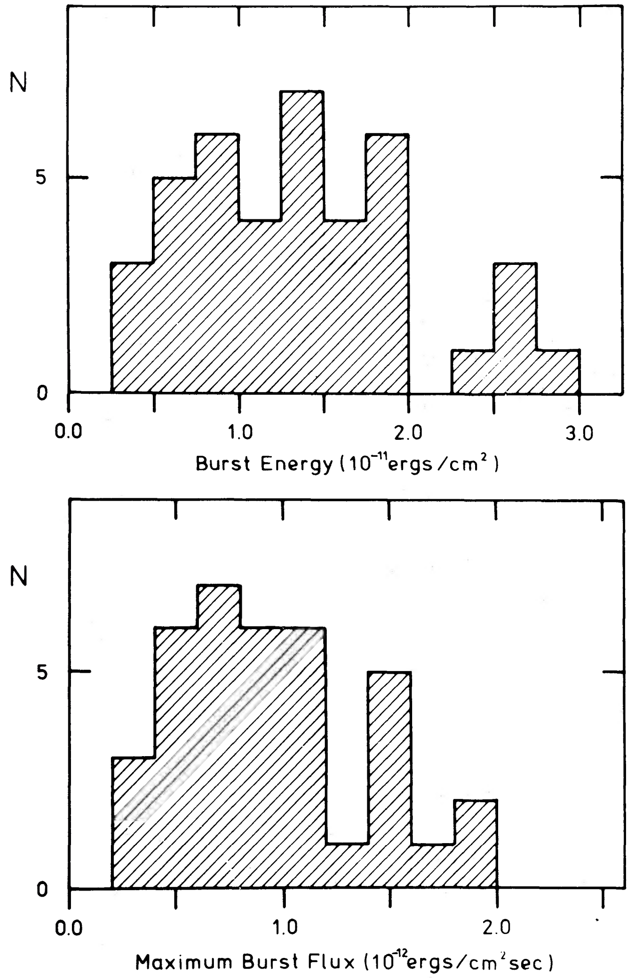

FIG. 3.—Histograms of the observed maximum burst fluxes (*upper panel*) and integrated burst fluxes (*lower panel*). Both quantities range over a factor of ~8.

burst fluxes, expected for this simple X-ray reprocessing model, is obtained by numerical integration of the time profiles of these artificial X-ray and optical bursts. We find that for a fixed value of T_0 the relation between the integrated optical and X-ray burst fluxes (the latter is determined only by the ratio F_1/F_0) is very well described by a power law with exponent $\beta = 0.65$. The scale factor in the power law is a decreasing function of T_0 since for hotter disks a larger fraction of the reprocessed X-rays emerge in the ultraviolet.

The difference with the observed value of 1.07 ± 0.19 may be significant. The observations suggest that perhaps more optical energy is emitted when the bursts are strong. The following effects might contribute to this result.

1. There may be a correlation between burst size and level of persistent emission, in the sense that the big bursts occurred when the persistent flux was systematically lower than for the small bursts. According to the blackbody reprocessing assumption, this would mean that then the persistent temperature of the region was lower and, consequently, optical photons would be emitted more efficiently (compared to ultraviolet photons). The available data do not, however show evidence for such a correlation.

2. The difference may be the result of the systematically smaller time intervals used in the integration of the total number of counts in the small bursts. We have investigated this possibility by making superpositions of seven small bursts (average value of $E_{opt} \sim 0.7 \times 10^{-11}$ ergs cm^{-2}) and seven large bursts (average $E_{opt} \sim 2.4 \times 10^{-11}$ ergs cm^{-2}). The average integration times are ~30 and ~80 s, respectively. It turns out that by cutting off the integration times at 30 seconds we have underestimated the integrated burst flux of the small bursts by ~12%, whereas those of the big bursts have been underestimated by less than 2% (on the average). This effect cannot account for the difference of a factor of ~2 between the observed and expected values of the power-law exponents.

b) *Burst Frequency*

Since the observations were optimized for the detection of optical bursts, the time spent on measuring the sky

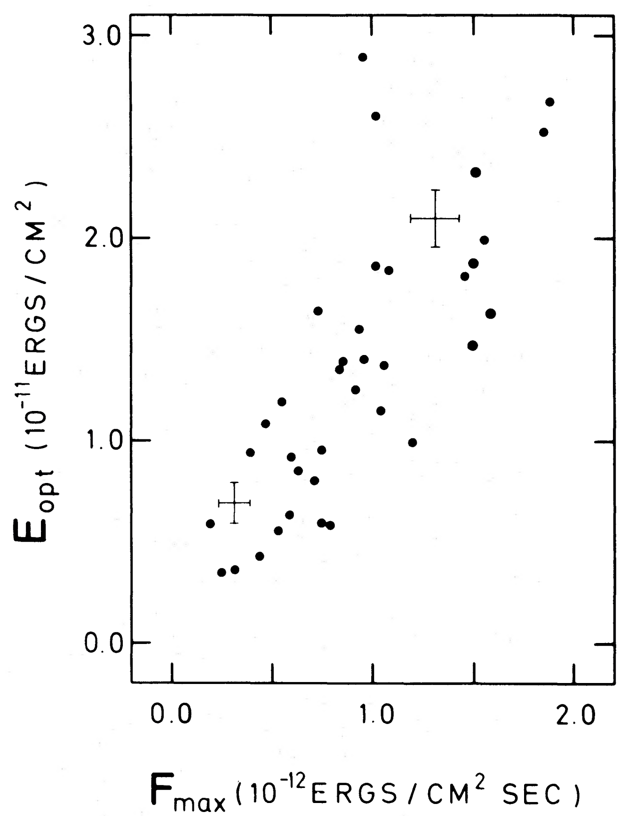

FIG. 4.—Relation between maximum and integrated optical burst fluxes (persistent optical flux subtracted). The two quantities are approximately linearly related, corresponding to an average burst duration $E_b/F_{max} = 15.3$ s.

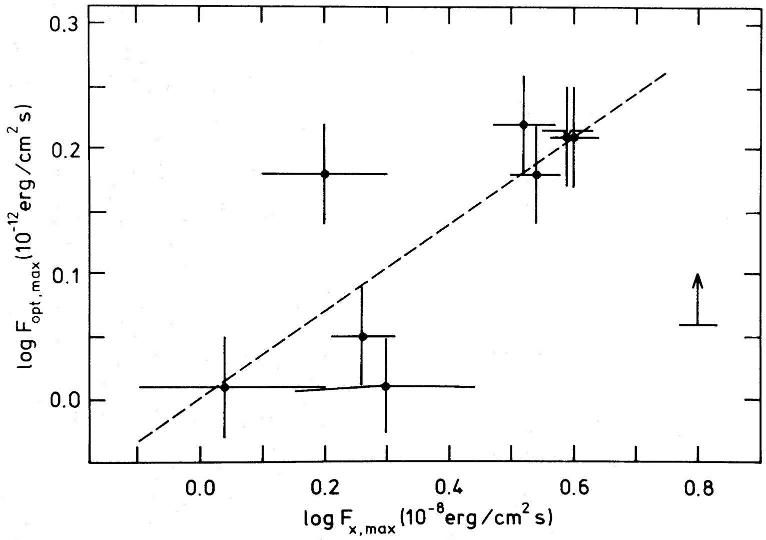

FIG. 5.—Relation between maximum optical and X-ray burst fluxes (including the persistent flux) for bursts observed simultaneously at ESO and with *Hakucho* (Ohashi 1981). The straight line drawn through the points corresponds to a power law $F_{\max,\mathrm{opt}}(:)F_{\max,X}{}^{0.34}$.

background and the calibration star was kept as short as possible. Furthermore, these measurements were usually taken a few minutes after the detection of a burst. In view of the fact that the time interval between consecutive bursts is typically 1 hr, the estimate of the waiting time until the next burst (even if a burst occurred during the sky or calibration measurement) is not seriously affected.

In Figure 7 we have plotted the integrated burst fluxes versus the time interval Δt since the *previous* burst, for those time intervals when the source was observed for more than 70% of the time (over half of the time intervals were covered for more than 90%; the remainder have a coverage which is approximately uniformly distributed between 70% and 90%). The two quantities are correlated, in the sense that bigger optical bursts tend to come after a longer waiting time. However, large variations in burst sizes do occur. Because of the correlation between the integrated optical and X-ray burst fluxes (see Fig. 4), one may expect that also the X-ray integrated burst flux on the average increases with the waiting time Δt.

This expectation is supported by Ohashi's (1981) observation that X-ray bursts from 4U/MXB 1636−53 which occur within less than 100 minutes after the previous burst tend to be smaller (by a factor of $\sim$2) than the average X-ray burst size.

The correlation between integrated burst flux and the time interval Δt since the previous burst suggested by the present data should not be confused with the linear

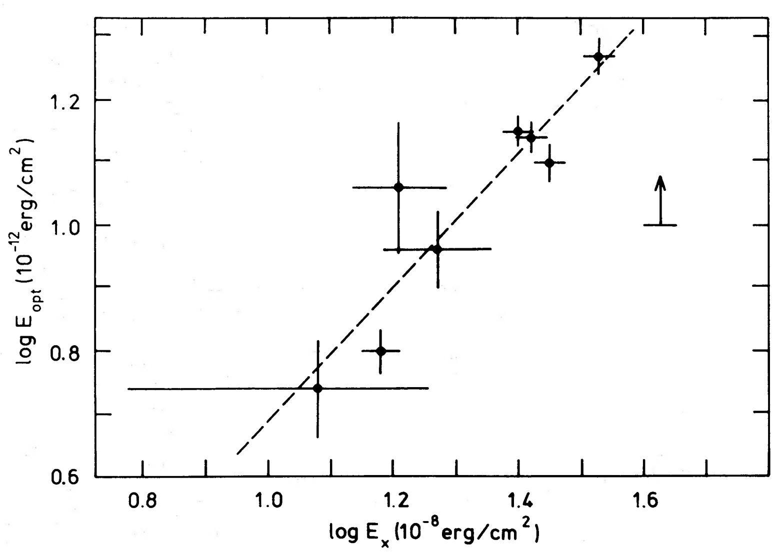

FIG. 6.—Relation between integrated optical and X-ray burst fluxes (persistent flux subtracted) for bursts observed simultaneously at ESO and with *Hakucho* (Ohashi 1981). The straight line corresponds to a power law $E_{\mathrm{opt}}(:)E_X{}^{1.07}$.

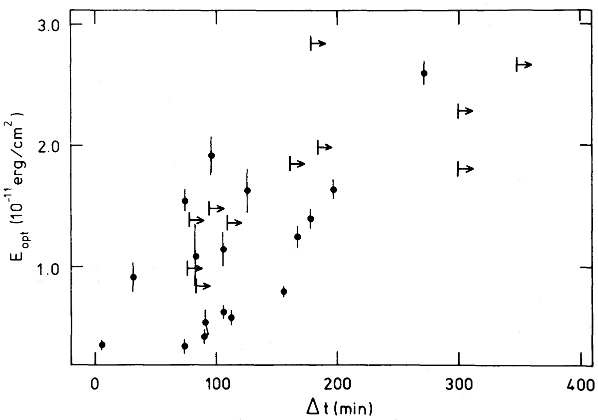

FIG. 7.—Relation between integrated optical burst fluxes and waiting time since the previous burst.

E-Δt relation established for the type II bursts (cf. Hoffman, Marshall, and Lewin 1978) observed from the Rapid Burster MXB 1730−335 (Lewin *et al.* 1976*a*). In the case of this source the relation is between the integrated burst flux and the time interval to the *next* burst. These two different E-Δt relationships for the type I and II bursts can be qualitatively understood as a consequence of the fact that the type I bursts are the result of thermonuclear flashes (a longer waiting time corresponds on the average to a larger amount of fuel available), whereas the type II bursts result from accretion instabilities (relaxation oscillator model: the time needed to refill a "reservoir" to a critical trigger level is proportional to the amount of matter released in the previous burst; cf. Lewin *et al.* 1976*a*).

Of particular interest is burst 28, which occurred only 5.5 minutes after burst 27. Burst 28 is quite small, but not much smaller than other optical bursts, for which a coincident X-ray burst has been detected. The reference optical signal did not show any deviation from a constant value. We are therefore convinced that this event is a bona fide optical burst.

Previously X-ray bursts have been detected at similarly small time intervals. Lewin *et al.* (1976*b*) observed three X-ray bursts from 4U/MXB 1636−53 are the same for all with time intervals of 17 and 24 minutes. Two X-ray bursts at a time interval of 10 minutes were detected from XB 1608−522 by Murakami *et al.* (1980), and recently two bursts at an 8 minute time interval were detected from XB 1745−24 (located in Terzan 5; Oda 1981). MXB 1636−53 again produced two X-ray bursts at a short time interval on 1981 June 15, UT 0048 and UT 0056 (Matsuoka 1982).

As discussed previously (Lamb and Lamb 1978; Ohashi 1981; Lewin and Joss 1981, 1982 and references therein), such small time intervals indicate that not all nuclear fuel is used up in a single thermonuclear flash. The amount of material accreted on the neutron star in ~10 minutes is not sufficient to provide the nuclear energy observed in the burst.

A "storage battery" model was suggested by Lamb and Lamb (1978), in which some fuel is stored (not burned). However, no scenario was presented as to how that might happen. Recent, detailed calculations (Ayasli and Joss 1982; Taam, 1980, 1981) suggest that a substantial fraction of the accreted hydrogen may be left over after a helium flash. This residual hydrogen may provide a plausible "storage battery." However, no one has yet shown theoretical model calculations, which reproduce the observed variability in burst intervals (including the very short ones).

Another way out of this problem is to assume that the X-ray bursts originate in different parts of the neutron star surface, each of which is triggered independently. However, arguing against this possibility is the fact that the apparent blackbody radii observed in the tails of the X-ray burst from 4U/MXB 1636−53 are the same for all bursts, irrespective of burst profile, burst size, or peak burst luminosity (Ohashi 1981; see also Lewin *et al.* 1980).

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L. Cominsky: Space Sciences Laboratory, University of California, Berkeley, CA 94720

A. Lawrence: Royal Greenwich Observatory, Herstmonceux Castle, Hailsham, E. Sussex, BN27 1RP, England

W. H. G. Lewin: Center for Space Research, Massachusetts Institute of Technology, Cambridge, MA 02139

M. Matsuoka, M. Oda, and T. Ohashi: Institute of Space and Aeronautical Science, 6-1, Komaba 4-chome, Meguro-ku, Tokyo 153, Japan

C. Motch and H. Pedersen: European Southern Observatory, Karl Schwarzschildstrasse 2, D-8046 Garching, West Germany

J. van Paradijs: Astronomical Institute, University of Amsterdam, Roetersstraat 15, 1018 WB Amsterdam, The Netherlands