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SIMULTANEOUS U, B, V, AND X-RAY MEASUREMENTS OF A BURST FROM 4U/MXB 1636−53[1]

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ABSTRACT

We present data on the first simultaneous X-ray and optical burst to be measured in more than one optical color. U, B, and V observations of 4U/MXB 1636−53 were made with the 3.6 m telescope at the European Southern Observatory, and the X-ray observations were made with the *Hakucho* X-ray observatory. Various analyses agree that to a first approximation, the optical burst is produced by blackbody reprocessing of the X-ray burst, with a short delay. The value of the delay is 2 or 3 s, depending on the technique used. The smearing of the optical signal is less than 3 s. The temperature of the optical reprocessor varies from ~ 25,000 K at quiescence to ~ 50,000 K at burst maximum. From the color-color diagram we derive an extinction toward the source of $A_v = 2.5 \pm 0.3$ suggesting a distance of $\gtrsim 2$ kpc. The projected effective area of the blackbody reprocessor is $\sim 5 \times 10^{21}$ $(D/5 \text{ kpc})^2$ cm^2. The fraction of the total X-ray burst energy which is converted into optical energy at all wavelengths is ~ 3%, within an order of magnitude. These parameters are discussed in light of a 4 hr orbital periodicity in the system reported by Pedersen, van Paradijs, and Lewin.

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

I. INTRODUCTION

Simultaneous X-ray and optical bursts were first detected from 4U/MXB 1735−44 (Grindlay *et al.* 1978; McClintock *et al.* 1979) and subsequently from MXB 1837−05 (= Ser X-1) (Hackwell *et al.* 1979). Ten simultaneous X-ray/optical bursts have been observed in "white" light from 4U/MXB 1636−53 (Pedersen *et al.* 1982*a*, *b*). In all cases the optical burst trails the X-ray burst by a few seconds, and the ratio of integrated flux in optical/X-ray bands is far too large for the optical emission to be explained as the blackbody tail of the X-ray burst. These considerations suggest that some fraction of the energy emitted by the X-ray burst is absorbed by nearby material and reemitted at optical wavelengths, and that the delay is due to light travel time differences, or reprocessing physics (McClintock *et al.* 1979; Pedersen *et al.* 1982*a*). The reprocessor may perhaps be the atmosphere of a stellar companion, or an accretion disk surrounding the X-ray source.

As McClintock *et al.* (1979) first pointed out, for relatively neutral matter, and the soft X-ray spectrum typical of an X-ray burst, physical reprocessing times must be fairly short as the X-rays are absorbed at small optical depths. Reprocessing times may be somewhat longer in very hot highly ionized material. Pedersen *et al.* (1982*a*) presented detailed arguments that the intrinsic delay involved in the reprocessing itself must be smaller than the values observed in the case of either a stellar companion or accretion disk. The delay then provides information about the system geometry. If one further assumes that the emerging optical radiation is Planckian, it is possible, using a nonlinear least squares method, to determine the temperature of the reprocessor as a function of time, and an optical "response function" resulting from the size, shape, and inclination of the reprocessing region. An analysis of one particular simultaneous optical/X-ray burst detected in white light with good signal-to-noise ratio in 1979 June enabled Pedersen *et al.* (1982*a*) to come to the following conclu-

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sions based on the simple single temperature blackbody instantaneous reprocessing picture:

(1) The temperature of the reprocessing region ranged from $< 3.2\times10^4$ K during quiescence to $7(+11, -2)\times 10^4$ K at burst maximum. (2) The optical response function could be well characterized by a delay and a smearing, both with a formal best fit value of ~ 3 s, although the smearing parameter was consistent with 0.0 s. (3) A good fit could be obtained by assuming that all of the persistent optical emission was due to reprocessing of the persistent X-rays.

In this paper, we report the detection of the first X-ray burst to be simultaneously recorded in the three standard Johnson passbands, U, B, and V. The main purposes of this report are to examine the validity of the blackbody reprocessing picture and to derive its main parameters, in a manner as accessible as possible to direct interpretation. First, we examine the track of the burst in the two-color diagram (i.e., $U-B$ versus $B-V$). From this we can obtain roughly the temperature of the optical emitter as a function of time, and the reddening to the source. Second, we examine the track of the burst in the [log (optical) versus log (X-ray)] plane for each color, and compare the results with predictions based on folding a Planck curve for various temperatures through the actual U, B, V response curves. Third, we cross-correlate the optical and X-ray data. This provides a model-independent value for the delay and shows that it is approximately the same for all three optical colors. Overall the agreement with the simple blackbody picture is surprisingly good; but there are differences in detail that will be important in future, more sensitive observations. Finally, we discuss the physical conclusions that can be inferred regarding the nature of the 4U/MXB 1636−53 system in the light of a newly discovered possible 4 hr periodicity in the optical light (Pedersen, van Paradijs, and Lewin 1981).

II. OBSERVATIONAL DETAILS

The observation of 4U/MXB 1636−53 described here was made as part of the 1980 worldwide burstwatch (Lewin and Cominsky 1980). X-ray observations were made with the *Hakucho* satellite. Optical observations were made with the ESO 3.6 m and Danish 1.5 m telescopes at La Silla, Chile. A total of 26 optical bursts were detected, five of them in coincidence with X-ray bursts. (No X-ray observations were made simultaneously with the other 21 optical bursts.) One particular burst (1980 June 18, 0355 UT) detected at U, B, and V with high signal-to-noise ratio, is of the most immediate interest and is reported and discussed in this paper. An analysis of all 41 optical bursts detected in 1979 and 1980 is presented in Pedersen *et al.* (1982*b*). A further analysis of simultaneous white light/X-ray bursts is in progress.

a) *X-Ray Observations*

The X-ray observations of 4U/MXB 1636−53 were made with the burst monitor detectors of the *Hakucho* X-ray observatory (Kondo *et al.* 1980). This system consists of two rotating modulation collimators, with circular fields of view 17°.6 and 5°.8 FWHM, as well as a tubular collimator, of field of view 5°.8 FWHM. The data presented here are from the tubular collimator (FMC-2); the non-source background was removed by mapping the region with the Fine Modulation Collimator (FMC-1). Two broad energy channels are available, with commandable boundaries. The channels used in this observation were (1–9 keV) and (9–22) keV.

There is much evidence that the X-ray spectra of type I bursts (Hoffman, Marshall, and Lewin 1978) are well approximated by blackbodies in the temperature range 1–3 keV (Swank *et al.* 1977; Hoffman, Lewin, and Doty 1977*a*, *b*; Cominsky 1981). Under this assumption, we find, by folding blackbody spectra through the known detector response function, that the bolometric X-ray flux can be represented by a linear combination of the counts in the two channels to within a few percent (see discussion in Pedersen *et al.* 1982*a*). Throughout this paper we use the following relation: bolometric X-ray flux density $F_{\rm bol} = F(1\text{–}9\ \text{keV}) + 4\times F(9\text{–}22\ \text{keV})$.

b) *Optical Observations*

The observations of the optical counterpart of 4U/MXB 1636−53 were obtained from the ESO 3.6 m telescope at La Silla on 1980 June 18. The photometer was a simultaneous four-channel instrument equipped with uncooled RCA 8575 photomultipliers. For the presently described observations, the photometer was used with a combination of beamsplitters and filters which fairly well reproduces the UBV system. The largest deviation from the standard UBV system (Allen 1973) is found in the transmission curve for the B band which, according to laboratory measurements, has an effective wavelength ~ 15 Å too short and an FWHM ~ 30 Å too narrow. In order to increase the optical throughput the depolarizing Glan prism was removed from the photometer.

Measurements in all three channels were affected by a rather high dark current (~ 50 counts s^{-1}) and by noise spikes. Since the spikes occurred on the integration timescale of 20 ms, it has been largely possible to remove their influence on the data (see § III).

Data acquisition was done using a "fast photometry" computer program. No time was lost between the integrations which lasted 20 ms each. UTC time codes and millisecond pulses from ESO's Atomic Beam Caesium Frequency Standard clock were monitored by the acquisition computer. Timing information was written on magnetic tape together with the photometric integrations.

TABLE 1

DERIVED PARAMETERS

Parameter	"Best Value"	Tolerance
Extinction, A_v	2.5 mag	± 0.3 mag
Distance	2–10 kpc	
T (persistent)	2.5×10^4 K	$> 10^4$ K
T (maximum)	5×10^4 K	$< 10^5$ K
Optical brightness	U (persistent) = 17.92 U (maximum) = 17.37	± 0.06
	B (persistent) = 18.47 B (maximum) = 17.48	± 0.03
	V (persistent) = 17.89 V (maximum) = 17.12	$\pm .03$
Delay	2–3 s	Depends on technique
Smearing	< 3 s	...
Bolometric X-ray integrated flux density	2.65×10^{-7} ergs cm^{-2}	$\pm 0.15 \times 10^{-7}$ ergs cm^{-2}
Bolometric optical integrated flux density	10^{-8} ergs cm^{-2}	One order of magnitude
Optical reprocessor blackbody effective area	$5 \times 10^{21} \times (D/5 \text{ kpc})^2$ cm^2	One order of magnitude

Guiding was done by optimization of the telescope tracking rate and by occasional checks of the source's position on the "large field" TV monitor. The progress of the observations was followed on a pen recorder which displayed the signal in the B channel at a time resolution of 8 s.

Sky measurements were taken at a position nominally 12″ E and 1″ N of the source. For the burst in question, the data were reduced using a 140 s long sky measurement which was started 8 minutes after the onset of the burst. Thereafter the source was carefully recentered. The following sky-corrected count-rate levels were 7% ± 3% higher in all three channels than the similar values determined prior to the burst, implying a slight miscentering of the source during the burst. The star approximately 7″ north of 4U/MXB 1636−53 was, however, never in the aperture.

The night 1980 June 17–18 was cloudless. The seeing was fine, 1″–2″, permitting the use of a 10″ diameter diaphragm throughout the night. The moon had set when the burst occurred.

A photometric calibration, including a correction for the source's miscentering, was obtained via observations of the stars Wolf 485A, Feige 108, and BSD 110−289. *UBV* values of these stars were taken from Eggen and Greenstein (1964) and Landolt (1973). Zero points were taken from Hayes (1979).

The photometric reduction disregards differences between the instrumental and standard system and also possible effects of polarization due to the photometer being used without its depolarizer.

The deduced magnitudes are given in Table 1.

III. DATA PROCESSING PROCEDURES

The major uncertainty in the X-ray data is due to counting statistics. There is some uncertainty in subtracting the nonsource background, but compared to most of the burst, the background is fairly small. For the optical data the background contributed ~ 65%–75% of the total quiescent count rate in any of the three colors. The various sky measurements spread through the night indicate that the background varied only slightly. We believe, therefore, that a sky measurement initiated 8 minutes after the onset of the burst is representative of the background during the burst. In general, we cannot, however, distinguish small changes in the star's brightness from sky background fluctuations. Accordingly, throughout this paper we express confidence only in optical features which are correlated with corresponding X-ray features.

The major uncertainty in the optical data is due to instrumental background noise. The average count rate due to the instrumental noise is ~ 50 counts s^{-1}, but the noise distribution has a long tail; i.e., there are occasional "noise spikes," some very large, and some comparable to the signal. As the "spikes" occurred on the integration time scale of 20 ms, most of them could be identified and removed. However, because of the overlap between noise and signal distributions, the cleaning process cannot be perfect. Also, the large noise means that estimates of count rates on short timescales (< 1 sec) have considerable errors; but averaging over much longer than a few seconds destroys information on timescales of interest in the burst. We desire, therefore, a

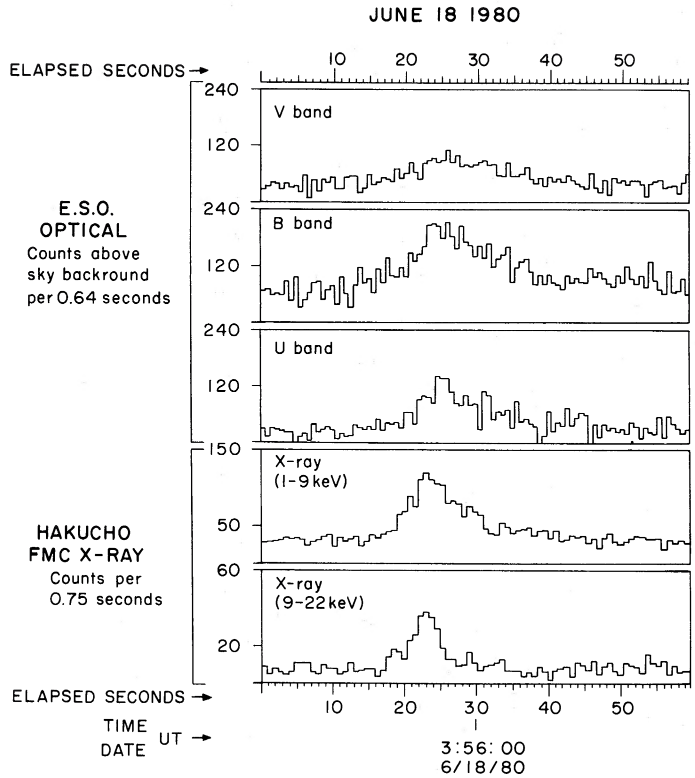

FIG. 1.—Simultaneous optical (ESO) and X-ray (*Hakucho*) data for the burst from 4U/MXB 1636−53 on 1980 June 18 0355 UT

data processing procedure both to clean and to smooth the data.

In order to assess the possible systematic errors involved, we have experimented with many different procedures, including moving average filters of various widths and weight functions; removing data points above a fixed count rate decided by visual inspection; removing all points a fixed number of standard deviations above the local average; median filters of various widths; and an iterative median filtering repeated until a stable sequence was reached. We find that, at the low count rates pertaining to our original 20 ms integrations, no filter gives both a "clean" output and an unbiased estimate of the local mean count rate of the signal, but that rather each possible procedure tends to be efficient at achieving just one of these two possible goals. For example, if one removes points a fixed number of standard deviations above the local average, then, for a Poissonian signal distribution, the fraction of the signal counts accidentally removed depends on the (unknown) mean signal count rate. This will be different between sky and sky plus source, resulting in a systematic error in background subtraction. If one makes the required number of standard deviations large enough to render the systematic error negligible, many of the smaller "noise spikes" will be left in and thus will mask real information.

A twofold approach was eventually used; quantitative estimates come from "unbiased but noisy" methods, but searches for, and validation of, interesting features was performed by using "biased but clean" methods (and by visually correlating with X-ray features). Figure 1 shows the sky subtracted "semi-raw" data. The largest "noise spikes" were removed and the data averaged in 0.64 s bins. The X-ray data are averaged in 0.75 s bins. The resulting optical data train is fairly unbiased, but its variance is ~ 50% larger than expected from counting statistics, and somewhat asymmetrical. For the cross-correlation analysis these "semi-raw" data were used directly. For the $[U - B$ versus $B - V]$ analysis and the [log (X-ray) versus log (optical)] analysis, a Gaussian moving average filter was first applied to both the optical "semi-raw" data and the X-ray data.

IV. ANALYSIS AND PHYSICAL INTERPRETATION

a) *General Correspondence between Optical and X-Ray Bursts*; *Estimation of Delay and Smearing*

A naive blackbody reprocessing picture, in which the optical passband is always on the Rayleigh-Jeans tail of the blackbody emission from the reprocessor, would require that at each time t, $F^{\alpha}_{\rm opt}(t) = F_x(t - d)$, where d is the delay, and $\alpha = 4$. In § IV*b* we shall find that the

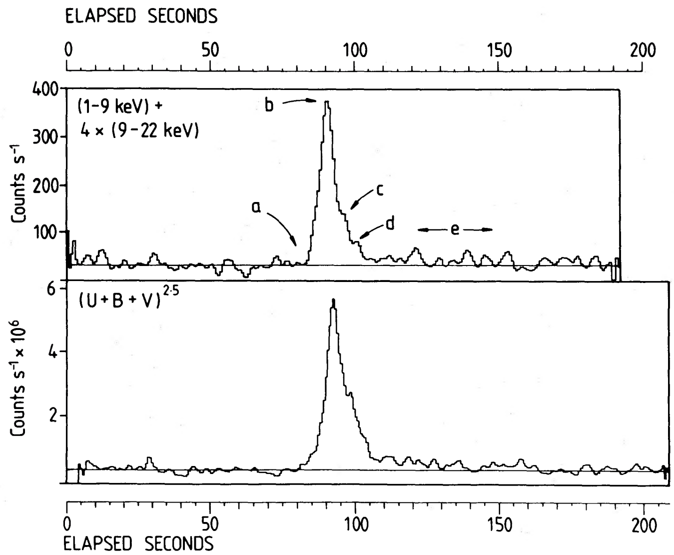

FIG. 2.—Bolometric X-ray data and "quasi-bolometric" optical data. Both data trains were smoothed with a Gaussian of FWHM = 2 s. The optical data were then raised to the power 2.5 and scaled so that optical and X-ray peaks are the same height. The labeled arrows refer to features discussed in the text (§ IV*a*).

temperature of the reprocessor ranges from $> 10^4$ K to $< 10^5$ K. In this range of temperatures, all three optical bands are close to, but not on, the Rayleigh-Jeans tail. The value of α at any point is then, of course, wavelength- and temperature-dependent, but a numerical experiment shows that $\alpha = 2.5$ is a good average fit through this region (see § IV*c*).

We can use these assumptions to get a visual impression of the general correspondence between the X-ray and optical bursts. Figure 2 shows bolometric X-ray counts derived as explained in § II*a*, together with the sum of counts from U, B, and V channels, raised to the power 2.5 (which should be, to first order, proportional to the bolometric optical flux density of the burst). Both data trains have been smoothed with a Gaussian of FWHM = 2 s. The correspondence is remarkably close. There are several distinct features in the X-ray burst which are also present in the optical burst, but delayed by ~ 2 s. As discussed in § III, the weak optical features would not be believed without the correlated X-ray features. We also find that the features discussed are invariant under the various cleaning procedures. We now discuss several labeled features in a semiquantitative fashion.

(1) The overall proportions of rise and decay are very similar. (2) The peak, "b," is delayed by ~ 2 s. (3) Two shoulders, "c" and "d", are also delayed by ~ 2 s. (4) There is a distinct "tail," "e," lasting 1 minute, of excess counts above the background fitted before the burst. (5) Detailed numerical correspondence of the rise and decay is more complicated. Figure 3 shows the main part of the burst in more detail. The X-ray burst has been plotted together with the optical burst, delayed by 2.0 s and scaled to the same peak value. The dominant optical rise fits well, but there is an initial optical excess in the first 4 s. Similarly, there is an optical excess in the latter half of the decay. This appears to suggest that the optical reprocessing function has considerable width, i.e., that the optical burst is smeared as well as delayed. However, as the optical emitter gets hotter and then cooler again during the burst, we may expect that our

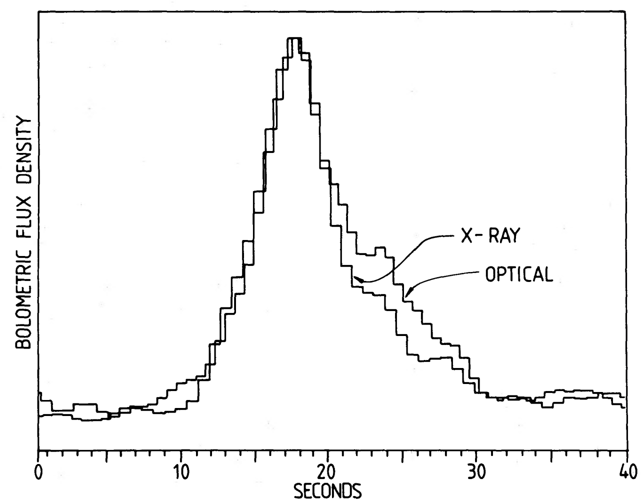

FIG. 3.—Bolometric X-ray data, delayed by 2.0 s, plotted together with "quasi-bolometric" optical data, scaled to equal peak heights. Both data trains are smoothed with a Gaussian of FWHM = 2 s.

crude bolometric correction is an underestimate near burst maximum, and an overestimate near quiescence (i.e., α is changing with time). This would produce an discrepancy in the direction observed. In § IV*b*, we derive information on the temperature profile of the burst, but this is not of sufficient quality to make a very significant improvement in the bolometric correction.

We may define the reprocessing function $P(t)$ by the optical bolometric energy as a function of time that would result from a delta function X-ray input at $t = 0$. It has a peak at $t \sim 2$ s. This value is fairly tightly constrained when directly matching the upper portions of the smoothed curves, as in Figure 3. However, there may be a small systematic effect produced in the smoothing process if the shapes of the optical and X-ray bursts are not quite the same. We also directly compared the unsmoothed versions. Because of the noise, the result is somewhat less certain, but the delay could be as small as 1.5 s or as large as 2.5 s. We do not attempt here to measure a "smearing parameter" in the sense of a formally defined "width" of $P(t)$. However, we note that the greatest difference in width between bolometric optical and X-ray burst profiles is 3 s. Given that a more accurate bolometric correction will tend to remove some of the discrepancy, this is an upper limit on "smearing" in the sense that $P(t > 5\text{ s})$ must be small compared to $P(t = 2\text{ s})$.

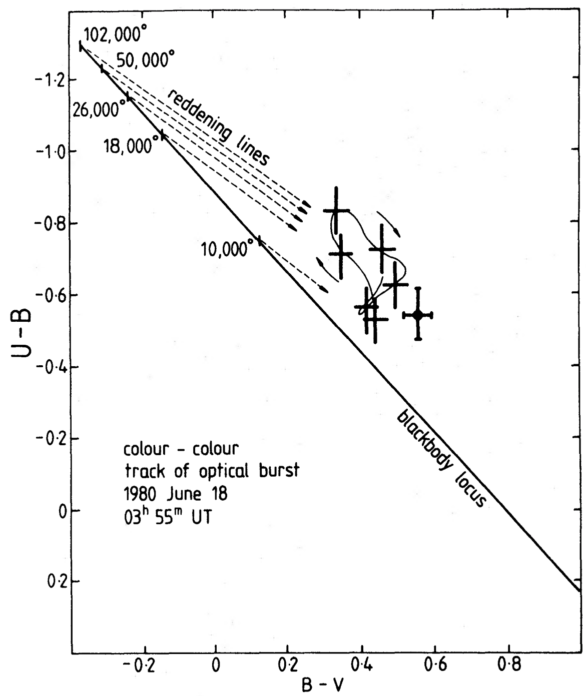

FIG. 4.—Track of the optical burst in the "color-color" diagram, i.e., $U - B$ vs. $B - V$. The data were first smoothed with a Gaussian of FWHM = 4.5 s before photometric reduction. The black line represents the overall smoothed track from burst rise until 35 seconds later. The crosses are individual points spaced such that they are (almost) independent of each other. The cross with a central circle is a preburst average. The indicated error bars are as in Table 1.

b) *Track of the Burst in the Color-Color Diagram; Derivation of Temperatures, Reddening, and Distance*

The optical data were converted to standard Johnson *UBV* magnitudes by comparison with standard stars as described in § III. Values of *U*, *B*, and *V* for the persistent source and the burst maximum are given in Table 1. The quoted errors are dominated by the fluctuations in the persistent source, which may or may not be actually due to sky background fluctuations. Figure 4 shows a smoothed version of the track of the burst in the color-color diagram, $U - B$ versus $B - V$. Seven individual points are also shown, with appropriate error bars, such that each point is (almost) independent of the points on either side. This emphasizes that, because of the smoothing, only the gross features of the track are meaningful.

Also plotted in Figure 4 is the locus of blackbody colors for various temperatures. This was obtained using the method of Mathews and Sandage (1963), and the actual measured U, B, V response curves, which are everywhere within a few percent of the standard curves. Notice that as the temperature increases past 10^5 K, the U, B, V passbands are all close to the Rayleigh-Jeans tail, and the blackbody colors do not change with temperature any more. We have also plotted reddening lines of slope $E_{U-B}/E_{B-V} = 0.72$ (see, e.g., Allen 1973), attached to various temperatures. An event describable at each point in time by a single blackbody temperature and a constant reddening should then produce a track parallel to the blackbody line, but displaced from it; a sliding fit should then enable us to read off E_{B-V} and the temperature evolution of the burst.

To first order, the overall track of the burst is indeed consistent with a reddened blackbody. We find T (preburst) $\sim 10^4$–(3×10^4) K and $T(\max) \sim (5 \times 10^4)$–$10^5$ K. To second order, there are definite complications. The rising part of the track is not the same as the decaying part. We cannot rule out a small background fluctuation on a short timescale at this point, or an incomplete subtraction of instrumental noise, so that we cannot be confident of the reality of the difference; but it may represent a real departure from the blackbody assumptions, perhaps even a variable reddening intrinsic to the system. The two "kinks" that can be seen in the decay (Fig. 2) correspond in time to the two shoulders, "c" and "d" (see § IV*a*). We are therefore confident that these are real because of their independent presence in the X-ray data. Finally, the colors do not appear to return to their "persistent" values by the end of the track presented in Figure 4. This corresponds to the tail "e" that lasts for a minute after the burst (see § IV*a*).

Each of the seven plotted points in Figure 4 can give an independent estimate of E_{B-V}. Assuming the errors to be normally distributed (which, however, is probably not the case) the mean value of E_{B-V} is quite well determined. We find $E_{B-V} = 0.8 \pm 0.1$, giving an extinction $A_v = 2.5 \pm 0.3$, assuming the standard value for the ratio of total to selective extinction of $R = 3.1$ (e.g., Allen 1973).

We emphasize that, because of the general agreement with reddened blackbody heating and cooling, we can have much more confidence in this estimate of A_v than any estimate possible from a single measurement. We can use the value of A_v to estimate the distance to 4U/MXB 1636−53. According to Lucke (1978) the reddening in this direction is $E_{B-V} = 0.4$ mag kpc^{-1}, which would indicate a distance $D \sim 2$ kpc. However, the dust layer in the Galaxy is only of the order ~ 150 pc thick (Allen 1973), so that the path length through extinguishing material in the direction of 4U/MXB 1636−53 is also ~ 2 kpc. Accordingly, the source may be either a disk object at ~ 2 kpc, or a halo object at some greater distance. A distance of about 5.5 kpc is found by assuming that the peak X-ray luminosity of an average burst (isotropic blackbody radiation) is constant and that the burst sources are, on the average, at a distance of 9 kpc (van Paradijs 1979). Following van Paradijs, Cominsky (1981) also assumed that all bursters are isotropic blackbody emitters at an average distance of ~ 9 kpc, but she assumed they all have the same radii. This leads to a similar distance to 4U/MXB 1636−53 of ~ 6.3 kpc. Probably, then, the distance to 4U/MXB 1636−53 is about 6 kpc; however, systematic errors may make this estimate rather uncertain (see Lewin 1982).

c) *Track of the Burst in the* [log (optical), log (X-ray)] *Plane*; *Estimation of Temperature Range*

Figure 5 presents $\log[F_{\rm opt}(t)]$ against $\log[F_x(t-d)]$ for each of the three optical channels. The data have been smoothed with a Gaussian of FWHM = 2 s. The value of *d* used was that derived from the cross-correlation analysis of § IV*d*, $d = 3.0$ s. Again we must note that because of smoothing, only the gross features are meaningful. The overall slope of the three tracks differ in a sense at least qualitatively in agreement with the blackbody hypothesis. It can be seen clearly that the *U* track is less steep than the other two. The *B* and *V* tracks have more similar slopes. "Eyeball" straight line fits yield power law slopes $\alpha_U \sim 2.0$, $\alpha_B \sim 2.7$, $\alpha_V \sim 3.0$.

From the color-color track (§ IV*b*) we know the range of temperatures applicable to the optical spectrum. Certainly T(preburst) > 10^4 K and T(max) < 10^5 K. For each temperature and filter, we may find $F_{\rm opt}(T) \propto \int_\nu B(\nu, T) R(\nu)$, where $B(\nu, T)$ is the Planck curve and

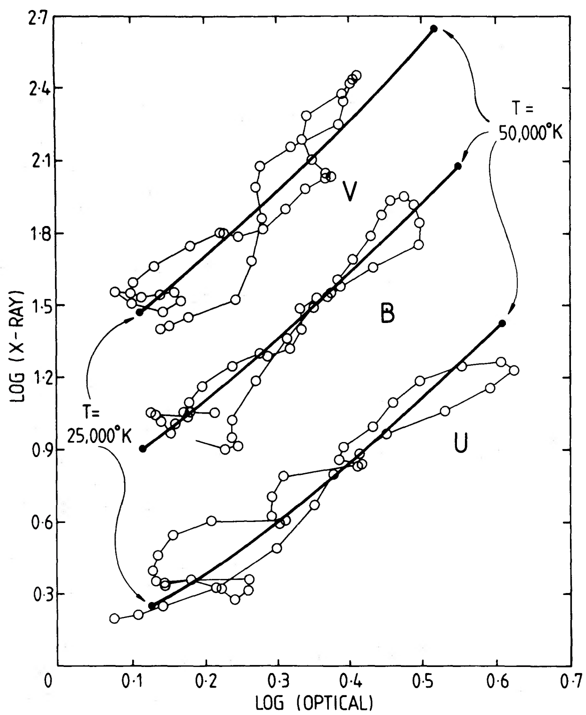

FIG. 5.—Track of the burst in the [log (X-ray) vs. log (optical)] plane for each of the three colors. Successive data points at 0.75 s intervals are marked by circles. Drawn through each observed track is a predicted track (*bold lines*) calculated by folding blackbody spectra with temperatures ranging from 2.5×10^4 K to 5×10^4 K, through the actual *U*, *B*, *V* response curves. The various tracks have been arbitrarily scaled for easy comparison; only the slope and range of each track is of importance.

$R(\nu)$ is the filter response curve. As $T^4(t+d) \propto F_x(t)$, we may predict the relation between $F_{\rm opt}(t+d)$ and $F_x(t)$.

To be consistent with both the observed average slope and the ratio of $F_{\rm opt}$(peak)/$F_{\rm opt}$(preburst) in all three cases requires that the temperature ranges only over a factor of 2 or so. A fairly close agreement with the observed tracks is obtained with the temperature ranging from ~ 2.5 to 5×10^4 K, as shown in Figure 5. The predicted tracks are actually slightly curved, but over this range are well approximated by power laws with $\alpha_U = 2.3$, $\alpha_B = 2.55$, and $\alpha_V = 2.8$. This temperature range is not precisely determined, but we can confidently state that 10^4–(2×10^4) K does not fit, and neither does (5×10^4)–10^5 K.

d) *Cross-Correlation Analysis*; *Derivation of Delay*

We cross-correlated the bolometric X-ray data with each of the optical channels in turn, and also with the summed optical data, for a 30 s interval containing the burst. The "semi-raw" data was used directly for this analysis. We also cross-correlated the persistent X-ray

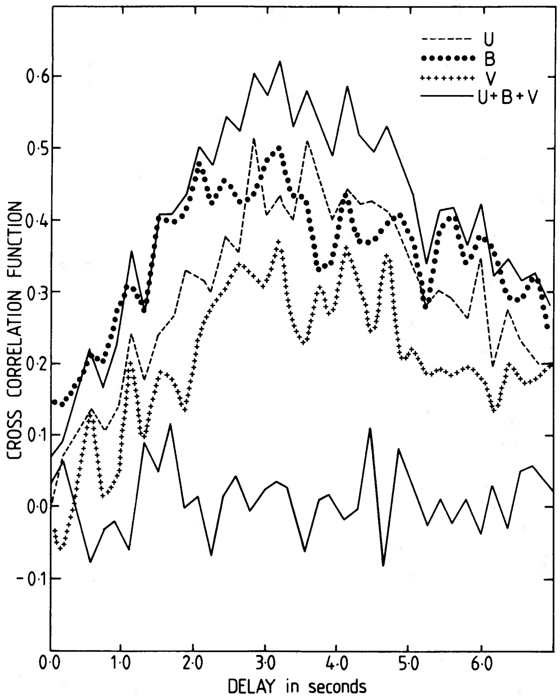

FIG. 6.—Cross-correlation functions between optical and X-ray data as a function of lag time. In each case the bolometric unsmoothed X-ray data was used at a time resolution of 0.1875 s. The cross-correlation function is presented separately for U, B, V, and for the sum of the three channels. The lower solid line is the cross-correlation function for the persistent optical/X-ray data immediately preceding the burst.

emission with the summed optical data for a 70 s interval immediately preceding the burst. The resulting standard normalized cross-correlation function for each case is displayed in Figure 6.

All that we consider here is the delay time which gives the maximum value of the cross-correlation function. It provides a well-defined measure of a characteristic "delay" which does not depend on the assumptions of blackbody reprocessing, or any other model fitting, but is in accordance with the intuitive concept of "delay." In general this value may be different from the characteristic "delay" of a blackbody reprocessing picture, i.e., the peak of the reprocessing function as discussed in § IV*a*. We find, however, that cross-correlating F_x with ${F_{\mathrm{opt}}}^{2.5}$ instead of F_{opt} makes little difference to the measured delay; we also find that it is affected very little by the addition or subtraction of a constant component.

There is some evidence that the delay is in fact slightly different in the three channels, in the sense $d(V) > d(U) > d(B)$. To first order, however, all three channels and the summed data are consistent with one value of $d = 3.0 \pm 0.5$ s. This agrees well with the delay of 3 ± 1.5 s obtained for the 1979 burst by Pedersen *et al.* (1982*a*). This might be fortuitous, however, as a similar analysis of all bursts detected both in X-rays and white light during 1979 and 1980 seems to indicate that the delay varies from ~ 1 to ~ 4 s (analysis in progress). We note that the overall correlation for summed data is better than that of any of the three individual channels. This is probably because both noise fluctuations and real deviations from simple reprocessing will tend to cancel out in the summed data.

Both the cross-correlation analysis presented in this section and the blackbody modeling procedure used by Pedersen *et al.* (1982*a*) utilize the X-ray and optical burst profiles in a "global" sense. We found, however (§ IV*a*), that lining up the X-ray and optical peaks requires a shorter delay, $d \sim 2 \pm .5$ s. The two results are marginally inconsistent. Such a difference may be expected if the optical reprocessing function $P(t)$ has a long tail toward large delay times. A "local" procedure, such as matching the X-ray and optical burst maxima, will be sensitive to the peak of $P(t)$. A global procedure will tend to find the expected value, $\langle t \rangle = \int_0^\infty P(t)\, dt$, which for an asymmetric $P(t)$ will always be larger than t_{peak}. This need not be inconsistent with the requirement of small smearing (§ IV*a*); the discrepancy may result from a little reprocessing at large delay times, as opposed to a lot of reprocessing at moderate delay times. Such a long-tailed $P(t)$ cannot easily result from simple geometrical reprocessing from an accretion disk or companion star, however, and would imply long physical reprocessing times for a small portion of the input energy—perhaps hard X-rays absorbed deep in the reprocessor.

The cross-correlation function for the persistent emission shows no peak at $d = 3.0$ s, which is perhaps surprising as we may expect that much of the persistent optical light probably also results from reprocessing of persistent X-rays. Indeed, it is an assumption of much of our analysis (though not a numerically crucial one). No individual fast fluctuations in the X-ray data are apparent to the eye, but small amplitude fluctuations could still produce an effect in the cross-correlation of a substantial segment. The lack of correlation probably tells us simply that the extra variance in the optical data due to non-Poissonian noise and sky fluctuations dwarfs any intrinsic variations in the star. The question of what fraction of the persistent optical light is due to reprocessed X-rays, and what to some other mechanism, is then left open.

V. DISCUSSION

Several lines of investigation agree that, at least to first order, the physics of the optical/X-ray burst is quite well described by a single temperature blackbody reprocessing model with a finite delay. There are also indications that this simple picture breaks down in places:

(*a*) The rising and decaying parts of the burst track in the color-color diagram are not the same. (*b*) The slope of the burst track in the color-color diagram changes at the position of two "shoulders" in the burst profile. (*c*) The slopes of the tracks of the three colors in the F_{opt} versus F_x diagram do not agree exactly with blackbody predictions.

We suggest two possible reasons for deviations. First, the spectrum of a simple reprocessor may be close to, but not quite, Planckian at each instant in time. A good example is the optical appearance of ordinary stars. To first order, stellar continua approximate blackbodies quite well. A closer look reveals differences that are a function of temperature (e.g., the Balmer continuum in absorption appearing in the *U* band). Second, we may have a complex reprocessor, each elemental surface of which behaves as a simple blackbody reprocessor; but as each elemental area is at a different distance and inclination angle from the X-ray source (and the observer), we see at each instant a blended spectrum averaged over time and space. If, at each moment in time, the low- and high-temperature regions have comparable areas, such a summed spectrum will be dominated by the hottest region. Thus, again, it may be that a complex reprocessor is fairly well represented by a single temperature Planckian. This will not, however, be the case for all complex reprocessors.

It is then at least of preliminary relevance to use parameters from a single-temperature blackbody model to calculate quantities of interest in the 4U/MXB 1636−53 system. Some of these are given in Table 1. We can define a blackbody effective area A such that

$$F_\nu = \frac{A}{D^2} \times B(\nu, T),$$

where F_ν is the flux density observed at Earth, D is the distance to the source, and $B(\nu, T)$ is the Planck function. This was separately estimated at each of the seven independent points of Figure 4, for each color. The uncertainty was estimated by the spread in these values. The uncertainty is large, mostly because of the crude temperature determination. The bolometric flux density

$$F_{\mathrm{bol}} = \frac{F_\nu \sigma T^4}{\pi B(\nu, T)}$$

was estimated in a similar fashion and summed over the duration of the burst. The data were corrected throughout for the extinction derived in § IV*b*, assuming a standard reddening law. We may place these numbers in the context of other information about the 4U/MXB 1636−53 system, in particular the report by Pedersen, van Paradijs, and Lewin (1981) of a possible optical periodicity of ~ 4 hr. As Pedersen, van Paradijs, and Lewin point out, if this represents the orbital period of the binary system, and if we assume that the stellar companion to the neutron star X-ray source is a main-sequence star overflowing its Roche lobe (in order to power the X-ray source), then, using the relations of Paczyński (1971) both the mass of the companion, and the separation of the system, can be determined. As allowed values of the periodicity differ by ~ 0.5 hr, the mass of the companion $M_c = 0.4 \pm 0.05\ M_\odot$, and the separation $S = 1.6 \pm 0.3\ R_\odot$. At a given distance D kpc, the fraction of the persistent optical light contributed by such a companion star (allowing for the estimated extinction) would be $\lesssim 1\% \times (5/D)^2$ at *U*, *B*, or *V*.

The total energy in X-ray and optical bursts, the delay, the binary separation, the temperature, and the effective blackbody area are all in approximate agreement. A delay of ~ 3 s corresponds to a light travel distance of $\sim 1.5\ R_\odot \sim 10^{11}$ cm. A reprocessing area equal to the observed effective blackbody area of $\sim 5 \times 10^{21}$ cm^2 (assuming $D = 5$ kpc) placed at a distance of 10^{11} cm from the X-ray source would intercept ~ 4% of the X-rays for reprocessing into optical light. If all the received X-ray flux density corresponding to the maximum X-ray luminosity $L_x = 3.7 \times 10^{38}$ ergs s^{-1} (and assuming a distance of 5 kpc), is reprocessed by a surface at 10^{11} cm from the X-ray source, the expected blackbody temperature is 6.3×10^4 K. All of these estimates are within the limits we can place on the observed values. As the uncertainties in the parameters are large, this may not be surprising; but it does immediately confirm that the reprocessing occurs somewhere in the vicinity of the companion star, or perhaps an accretion disk around the X-ray source, and *not* (*i*) either very close to the X-ray source, or (*ii*) in a surrounding region much larger than the binary system. In particular, the consistency between the observed temperature range and that expected from a blackbody reprocessor at a distance given by assuming the delay to be a light travel time, rules out the possibility that reprocessing occurs in a very hot highly ionized region close to the X-ray source (McClintock *et al.* 1979).

A more crucial question is whether the surface of the companion star or the surface of a possible accretion disk dominates the reprocessing. The present data cannot enable a clear decision on this point but offers some interesting clues. First, consider the blackbody effective area. The surface area of either the companion or an accretion disk are both of the order $\sim 10^{22}$ cm^2. Within our tolerances, the effective blackbody area we have estimated may be as little as 5% of this possible area or as much as all of it. In the case of the companion star, it is easy to verify that this is about the right figure, by calculating how far around the stellar surface the optical "hot spot" should extend. Consider θ, the angle between the line joining the stellar center and the X-ray source, and the line from the stellar center to a given point on the stellar surface. Given the stellar radius and the binary separation distance, then for each θ we may calculate the energy absorbed per unit area, E_{abs}, allowing for the angle of incidence and the distance from the X-ray source. We may further assume that the emerging narrow band optical intensity $I_{opt} \propto E_{abs}{}^{0.4}$. Then, for the simple case of a distant observer viewing the "hot spot" face-on, we can calculate the surface brightness at each θ, $S_{\text{opt}} \propto E_{\text{abs}}{}^{0.4} \cos\theta$. For the numbers appropriate here we find that 90% of the emergent optical light should come from inside $\theta \sim 50°$. Thus the stellar "hot spot" covers about 18% of the stellar surface. For an accretion disk, a calculation is harder to make because of many critical unknowns. What is the shape of the disk? Is it azimuthally symmetric? Is it inclined to the line of sight? However, for estimates of temperature and delay to be consistent (see above) we know that most of the reprocessing must occur in the outer rather than the inner regions of any such disk. This probably rules out a standard thin disk, but it may be consistent with a "flared" disk, as envisaged, for instance, by Milgrom (1978) or Jones and Raine (1980).

The delay, $d = 2$–3 s, is consistent within our errors with either the companion star or the outer part of an accretion disk as discussed above. In the accretion disk case smearing is expected to be as large as the delay (cf. Pedersen *et al.* 1982*a*). Our estimation of smearing is only marginally consistent with this expectation. For the companion star, if the orbit is sufficiently inclined, we expect the delay to be variable from burst to burst and to correlate with the effective blackbody area. We note that, in order to explain the observed light modulation, Pedersen, van Paradijs, and Lewin (1981) postulate a "thick spot" in the disk at the point where matter from the companion star is injected. As a reprocessor, this "*thick spot*" could behave in a very similar fashion to the companion star. To address the question of variable delay, an analysis similar to that of Pedersen *et al.* (1982*a*), of all simultaneous optical/X-ray bursts from 4U/MXB 1636−53 in both 1979 and 1980, is in preparation. Preliminary results indicate that the delay is variable.

VI. CONCLUSIONS

Various methods of analyzing the simultaneous U, B, V, and X-ray data on a burst from 4U/MXB 1636−53 have shown that, with some detailed exceptions, X-ray reprocessing into optical light is reasonably represented by a single-temperature blackbody model. This allows us to calculate many quantities of interest. The optical temperature is $\sim 2.5 \times 10^4$ K at quiescence and $\sim 5 \times 10^4$ K at burst maximum. The extinction towards the source is $A_v = 2.5 \pm 0.3$. The distance D to the source is between 2 and 10 kpc. The effective blackbody area of the reprocessing region is $\sim 5 \times 10^{21}$ $(D/5\ \text{kpc})^2$ cm^2. The delay between X-ray input and observed optical output is 2–3 s, and the smearing of the optical signal is < 3 s. A few percent of the total X-ray burst energy is captured and converted to optical radiation. The periodicity of the source suggested by Pedersen, van Paradijs, and Lewin (1981) tells us the size of the system and the stellar companion to the X-ray source. Viewing this information together with the above estimates, the most feasible site for X-ray reprocessing is either the surface of the companion star, or the outer part of an accretion disk surrounding the X-ray source. It is important in further studies to search for possibly variable delays which may be expected if the accretion disk has an azimuthal asymmetry, such as suggested by Pedersen, van Paradijs, and Lewin (1981) to explain the optical light modulation. Whether the dominant reprocessor is the companion star or the "thick spot" in the accretion disk, in both cases one expects the ratio of optical to X-ray flux in a burst to vary periodically. Also, the optical delay would then vary together with the orbital period as earlier suggested by Pedersen, van Paradijs, and Lewin (1981).

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