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EXOSAT OBSERVATIONS OF 4U/MXB 1636−53: ON THE RELATION BETWEEN THE AMOUNT OF ACCRETED FUEL AND THE STRENGTH OF AN X-RAY BURST

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ABSTRACT

During *EXOSAT* observations of 4U/MXB 1636−53 in 1985 August, three bursts were observed in 6 hr and 24 bursts in 79 hr of uninterrupted observing. The persistent X-ray flux varied by about a factor of 2.4, the burst intervals by a factor of 24 (from 35 minutes to 14 hr), and the integrated burst fluxes (the burst fluences), and burst peak fluxes both approximately by a factor of 6. Very globally, the burst fluence is approximately linearly proportional to the interval (and to the integrated persistent flux) since the preceding burst, as long as we exclude the three bursts with the longest intervals which exhibit photospheric radius expansion. If in these cases a major fraction (up to about $\frac{2}{3}$) of the thermonuclear flash energy was consumed in mass ejection, the approximate linear relation would hold over the whole range of observed intervals if the burst fluences are corrected for this "lost" energy.

Independently, in the context of the thermonuclear flash models, all bursts suffer from nuclear energy losses due to stable hydrogen burning between the bursts. This provides a mechanism in which the percentage of "lost" energy increases with increasing burst intervals. This picture, combined with the above losses due to mass ejection, fits our data globally quite well. The energetics of the stable burning are discussed in detail in a companion paper.

For individual bursts, however, there are significant deviations (scatter) from the approximate linear relation. Fujimoto *et al.* suggest in the companion paper that this scatter is related to the longstanding problem of detections (from various sources) of burst intervals shorter than 10 minutes (for 1636−53 the shortest interval reported is 6 minutes). The accretion during these very short intervals is much too small to account for the observed bursts. A nuclear fuel storage model and a specific mechanism to ignite this fuel is discussed in some detail in the companion paper.

Subject headings: nuclear reactions — stars: accretion — stars: neutron — X-rays: bursts

I. INTRODUCTION

Precise studies of the relation between X-ray burst characteristics and the accretion between bursts are essential to our understanding of the complex physics of the thermonuclear flashes which are generally believed to produce the bursts (for reviews see Lewin and Joss 1983; Joss and Rappaport 1984, and references therein).

Hoffman, Lewin, and Doty (1977) first reported that there was probably a correlation in MXB 1728−34 between the integrated energy in and X-ray burst (i.e., the burst fluence) and the time interval since the preceding burst (the larger the interval, the larger was the burst fluence). This was confirmed by later observations (Basinska *et al.* 1984). For 4U/MXB 1636−53, Pedersen *et al.* (1982) observed a clear correlation between the optical burst fluence and the interval since the previous optical burst.

The X-ray studies were greatly hampered by the limitation in the duration of uninterrupted observations. Prior to *EXOSAT* all X-ray observatories were in near-Earth orbit. Thus most sources were occulted by Earth for typically about 30 minutes every 90–100 minutes. As an example, for *SAS 3*, on the average two of three bursts were detected. For *Hakucho* and *Tenma*, on the average, only two of 13 bursts were detected since most of the data was not retrieved (see Lewin 1985). In all cases where the burst could only be determined with certainty when they were shorter than about 1 hr and when no occultation occurred during that interval. Since most burst sources have irregular intervals, and the large majority of the intervals are in excess of 1 hr (for a review see Lewin and Joss 1983), the actual intervals are often (much) shorter than the observed ones.

The 91 hr orbital period of *EXOSAT* made it possible to determine unambiguously burst intervals of up to tens of hours and to study in detail their relation to the burst characteristics. Such studies were expected to give new information in the structure of the surface layers of accreting neutron stars where the thermonuclear flashes occur.

We report here on such a study of 1636−53. The observations are discussed in § II, the analysis, in § III. In § IV we discuss the results, and in § V, their implications for the models. Specific suggestions resulting from our observations are discussed in some detail in the companion paper by Fujimoto *et al.* (1987, hereafter Paper II).

II. OBSERVATIONS

The two *EXOSAT* observations presented here were made from 1985 August 6.81 UT to August 7.07 UT (6 hr), and from August 7.50 UT to 10.79 UT (79 hr); they were each made uninterruptedly. The gap in the data is due to spacecraft perigee. Data from the two medium energy proportional counter arrays (Turner, Smith, and Zimmermann 1981) have been used in the present analysis. Most of the time, the full array was pointed at the source. About 15 minutes after the occurrence of each burst, one of the two arrays was offset for about 20 minutes to measure the background. At least one array was always pointed at the source.

III. ANALYSIS

In Table 1 we list the burst times, the burst fluences (E_b), the peak burst fluxes (F_{max}), the burst rise times (τ_r), the decay times (τ_d), the burst intervals (Δt) (since the preceding burst), the mean persistent fluxes during that interval (F_p), the product of F_p and Δt, which is called E_p (it is the integrated persistent flux since the previous burst), and alpha which is defined as E_p/E_b.

In deriving E_b, and F_{max}, we followed the same procedure as described by Sztajno *et al.* (1985). Thus the values listed are bolometric and are corrected for deadtime. To calculate the bolometric persistent flux, we first evaluated the background of the two arrays separately as a function of time. The difference between the background in the two arrays was about 25%, but in each array it varied by less than 0.5% throughout the observations. The background was subtracted from the observed counting rates for each half array, and for each of the 31 energy channels, separately.

The resulting counting rates were averaged over approximately 10 minute intervals and fitted with a two-component (blackbody plus thermal bremsstrahlung) spectral model. In each interval, good fits (χ^2/dof less than 1.3) could always be found. The blackbody component, which contributed only about 10% to the total flux, had kT values between about 0.3 and 0.4 keV; in the thermal bremsstrahlung component kT varied between 6.3 and 8.4 keV. Approximate bolometric fluxes were found by integrating the fitted spectra from 1 to 20 keV, and the values for F_p and E_p were subsequently calculated.

We did not explore the various possibilities of two-component spectra (see, e.g., Swank and Serlemitsos 1985; Makishima and Mitsuda 1985; White and Mason 1985; White *et al.* 1986) as that was not the purpose of our investigations. Vacca *et al.* (1987) performed an extensive study of the many

TABLE 1

SOME PROPERTIES OF THE BURSTS AND THE PERSISTENT EMISSION

Number	Time[a] (days)	E_b[b] (10^{-7} ergs cm^{-2})	F_{max}[c] (10^{-8} ergs cm^{-2} s^{-1})	τ_r[d] (s)	τ_d[e] (s)	Δt[f] (hr)	F_p[g] (10^{-9} ergs cm^{-2} s^{-1})	E_p[h] (10^{-4} ergs cm^{-2})	Alpha[i]
1	6.84080	2.26	1.42	5.1	12.8	>0.6767	~1.513	>0.0368	>16.
2	6.96635	3.56	2.16	6.5	9.0	3.0133	1.429	0.1550	44.
3	7.05993	2.49	2.24	1.8	8.2	2.2458	1.423	0.1151	46.
4	7.50630	2.00	2.37	1.6	5.3	>0.1522	~2.015	>0.0110	>6.
5	7.58486	1.38	1.41	3.1	7.2	1.8856	2.099	0.1425	103.
6	7.62471	0.91	1.15	5.3	4.5	0.9564	2.202	0.0758	83.
7	7.67874	1.28	1.37	3.3	6.0	1.2967	2.158	0.1007	79.
8	7.85258	3.78	3.33	4.9	8.6	4.1722	2.176	0.3269	87.
9	7.94216	2.29	1.94	4.6	8.0	2.1500	2.193	0.1698	74.
10	8.09905	3.20	3.75	2.3	5.6	3.7653	2.188	0.2966	93.
11	8.43683	4.17	6.15	0.5	4.4	8.1068	2.433	0.7100	170.
12	8.53451	1.10	1.76	2.6	3.5	2.3444	2.429	0.2050	187.
13	8.67116	2.99	3.49	4.0	4.3	3.2794	2.539	0.2998	100.
14	8.71750	1.01	1.36	2.5	3.5	1.1122	2.558	0.1024	101.
15	8.76874	1.26	1.37	2.9	7.0	1.2297	2.444	0.1082	86.
16	8.90308	2.81	2.77	5.9	6.4	3.2242	2.497	0.2899	103.
17[j]	8.93234	...	...	...	...	0.7022	2.605	0.0659	...
18	8.97569	1.06	1.38	2.8	5.1	1.0406	2.552	0.0956	90.
19	9.18138	2.59	3.35	3.5	3.9	4.9364	2.653	0.4714	182.
20	9.24181	0.99	1.64	3.0	3.3	1.4503	2.820	0.1472	148.
21	9.40109	3.00	3.43	5.0	4.8	3.8228	2.955	0.4066	135.
22	9.44932	0.79	1.32	2.9	3.9	1.1575	2.885	0.1202	152.
23	9.50975	0.96	1.48	2.8	2.8	1.4503	3.004	0.1568	163.
24	9.53434	0.66	1.24	2.6	4.2	0.5908	3.267	0.0694	104.
25	9.62656	2.51	1.40	2.9	6.3	2.2133	3.215	0.2562	102.
26	10.21392	4.94	5.93	1.0	4.5	14.0967	3.418	1.7344	351.
27	10.77017	4.76	6.84	0.6	4.9	13.3500	3.327	1.5989	336.

[a] Burst time (days since 1985 Aug 1.00000); uncertainty is 2 s.
[b] Burst fluences (10^{-7} ergs cm^{-2}); uncertainties vary between 2% and 10%.
[c] Burst peak flux (10^{-8} ergs cm^{-2} s^{-1}); uncertainties vary between 7% and 14%.
[d] Rise time (s); uncertainties are about 10%.
[e] $1/e$ decay times (s); uncertainties vary between 15% and 23%.
[f] Burst intervals (hr); uncertainty is 3 s.
[g] Average persistent flux during interval Δt bursts (10^{-9} ergs cm^{-2} s^{-1}); statistical uncertainties are about 0.25%.
[h] Integrated persistent flux during interval Δt (10^{-4} ergs cm^{-2}); statistical uncertainties are about 0.25%.
[i] Alpha; uncertainties vary between 2% and 10%.
[j] Data incomplete.

acceptable combinations of two-component spectra for 1636−53. We know from their work that the many acceptable fits, other than those that we have chosen, do not lead to appreciably different values for F_p and E_p.

The burst risetime (τ_r) is defined as the time interval in which the observed count rate (1–20 keV) increases from 10% to 90% of the maximum observed count rate. The decay time (τ_d) is defined as the time needed for the bolometric flux to decrease from its maximum value to $1/e$ times that value.

In Figure 1 we plot the bolometric persistent flux averaged over 200 s intervals as a function of time; the times that bursts occurred are marked. In Figure 2 we plot F_{max} versus E_b to allow for an easy comparison with similar plots published for other burst sources. In Figure 3 we plot values for E_b, F_{max}, τ_r, τ_d, F_p, E_p, and alpha as a function of the burst intervals Δt.

In the framework of thermonuclear flash models, the amounts of accreted matter between bursts may be more relevant than the time intervals, Δt. If the integrated persistent flux E_p were linearly related to the gravitational potential energy released between the bursts, it might be a more useful parameter than Δt. (The observed deviations from linearity between Δt and E_p, shown in Fig. 3*f*, are the result of the variations in the observed persistent flux.) We therefore show in Figure 4 the quantities E_b, F_{max}, and alpha plotted versus E_p.

IV. DISCUSSION OF THE DATA

The maximum burst flux, F_{max}, is correlated with the burst fluence, E_b (Fig. 2). The relation is approximately linear as previously observed (Ohashi *et al.* 1982). However, large variations for individual bursts (up to factors of about 2), occur. A linear dependence was also observed in optical bursts from this source (Pedersen *et al.* 1982).

Such approximately linear relations, excluding those bursts that cause photospheric radius expansion, are common among the well-studied burst sources: 1735−44 (Lewin *et al.* 1980), Ser X-1 (Sztajno *et al.* 1983), and 1728−34 (Basinska *et al.* 1984). For the transient source 1608−52 an approximate linear relation was only observed when the source was bright; not when it was faint (Murakami *et al.* 1980). This may also have been the case for the transient 0748−676 (Gottwald *et al.* 1986).

There is some evidence in our data for a "gap" in the distribution of F_{max} (between roughly 3.5×10^{-8} and 6×10^{-8} ergs cm^{-2} sec^{-1}; see Fig. 2). This gap was first noticed by Ohashi (1981) and interpreted by Sugimoto, Ebisuzaki, and Hanawa (1984). In the complete set of F_{max} values from all observations (*SAS 3*, *Hakucho*, *Tenma*, and *EXOSAT*), including those reported here, the gap is very apparent (Fujimoto *et*

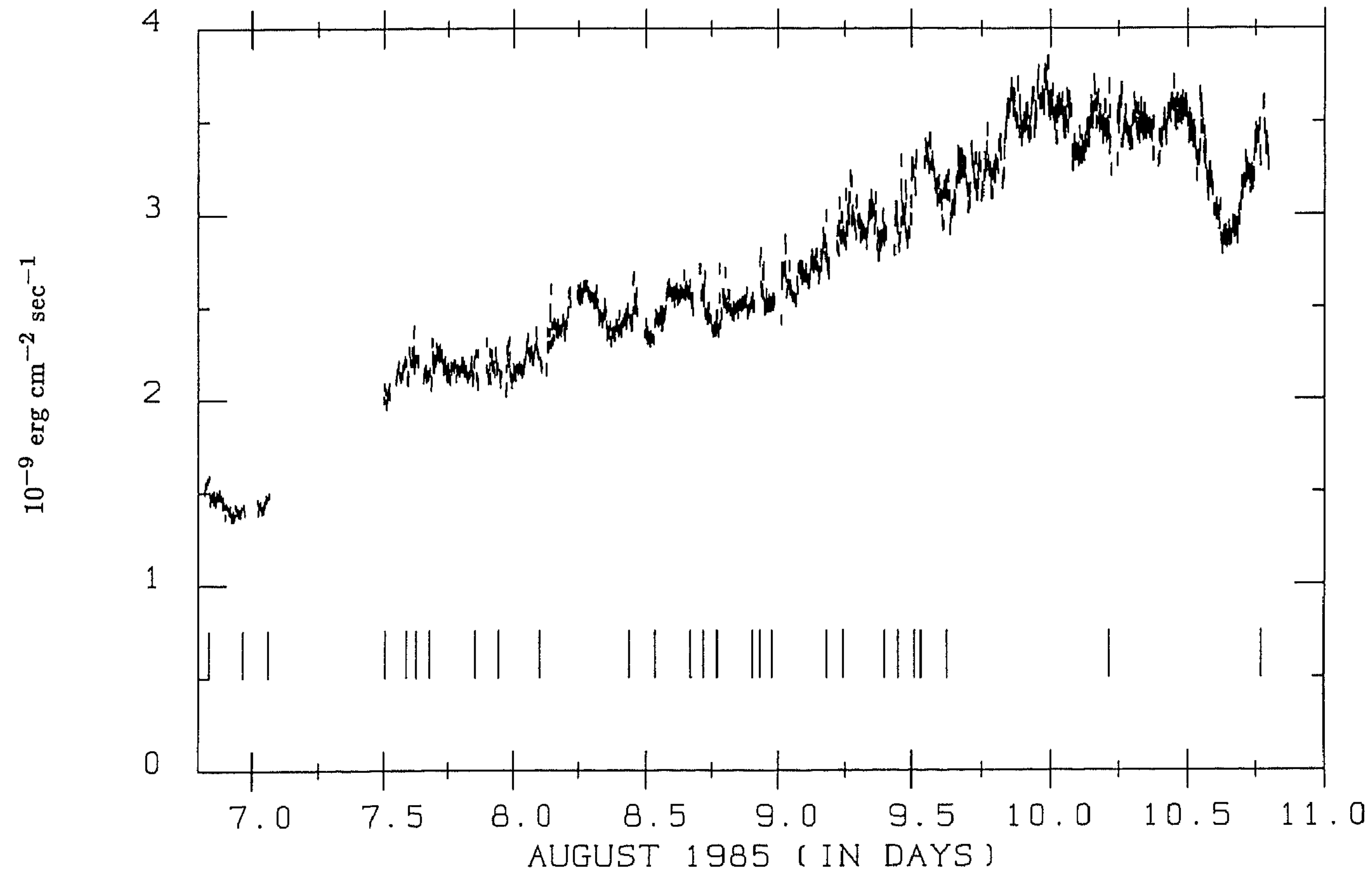

FIG. 1.—Bolometric persistent flux (deadtime corrected, and background subtracted) as a function of time. Each data "point" is an average value of approximately 200 s; statistical uncertainties are less than 1% in each point. The horizontal axis is marked in days in 1985 August. The burst times are indicated as vertical bars near the bottom. No observations were made between August 7.07 and 7.50 (spacecraft perigee).

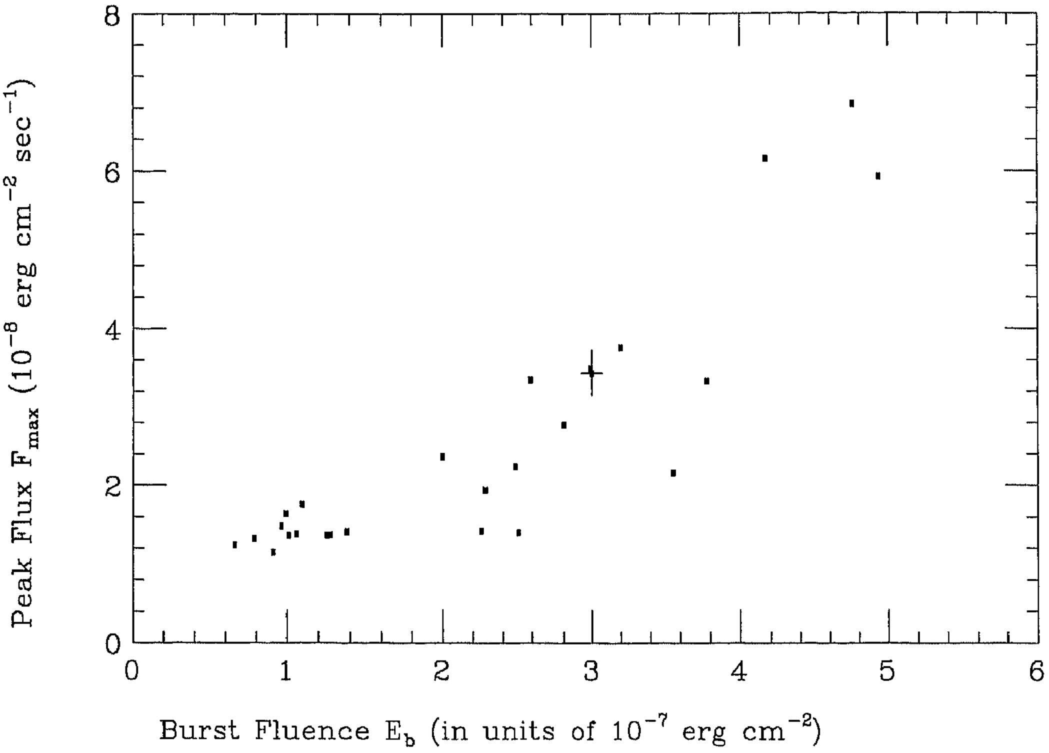

FIG. 2.—Bolometric peak burst fluxes (F_{max}) vs. bolometric burst fluences (E_b). A typical error bar is shown (see also footnotes to Table 1).

al. 1986*a*). Peak burst fluxes just below the gap are believed to be associated with the Eddington limit of a hydrogen-rich atmosphere, those above the gap with that of a hydrogen deficient atmosphere (Sugimoto, Ebisuzaki, and Hanawa 1984; Fujimoto and Taam 1986; see also Paper II).

A gap (in F_{max} distributions) is then expected only in sources from which a fair number of bursts (e.g., at least 10) has been detected, and for which at least one burst, but not all, unambiguously exhibit radius expansion. Three such sources meet these conditions; 1728−34 (Hoffman, Cominsky, and Lewin 1980; Basinska *et al.* 1984), and the transients 1608−52 (Matsuoka 1985), and 0748−676 (Gottwald *et al.* 1986). Gaps are not present in data from the first two sources, but there is evidence for a gap in 0748−676.

In our data of 1636−53 all three bursts above the gap (Fig. 2), caused a clear radius expansion, and we expect that all very energetic bursts from 1636−53 (i.e., with values for E_b in excess of about 4×10^{-7} ergs cm^{-2} will have "saturated" peak fluxes of about 6×10^{-8} ergs cm^{-2} s^{-1}. This would not be so if the anisotropy in the burst emission were varying significantly in time, but that is not the case (see below). (Details about the blackbody radii, and the observed photospheric expansion in the three bursts with the longest intervals, will be reported at a later date). Such a saturation in F_{max}, for every large values of E_b, is observed in 1728−34 (Basinska *et al.* 1984), and possibly also in 0748−676 (Gottwald *et al.* 1986). All bursts observed with *SAS 3*, and *EXOSAT* from 1820−30 (located in the globular cluster NGC 6624), showed radius expansion; they had all approximately the same peak fluxes, consistent with the Eddington luminosity of a helium-rich atmosphere of a 1.4 solar mass neutron star (Vacca, Lewin, and Van Paradijs 1986; Haberl *et al.* 1987). (For recent discussions about observed radius expansion, see Lewin 1984; Tawara *et al.* 1984; Lewin, Vacca, and Basinska 1984; Basinska *et al.* 1984, and references therein).

In Figure 3 various burst and persistent emission properties have been plotted versus Δt. Very globally, the longer the burst interval, the more energetic is the burst (Fig. 3*a*). This is in agreement with earlier results for optical bursts from this source (Pedersen *et al.* 1982) and with observation of 1728−34 (Hoffman, Lewin, and Doty 1977; Basinska *et al.* 1984; see also the Introduction above). A similar relation was also found in recent observations of 0748−676 (Gottwald *et al.* 1986).

Individual bursts show substantial deviations (scatter) from a linear relation; they do not disappear if we replace the burst intervals by the integrated persistent flux, E_p (Fig. 4*a*). This scatter, and the fact that the two bursts (burst 26 and 27) with the largest intervals (both show radius expansion) have the smallest slopes $E_b/\Delta t$, and E_b/E_p (Figs. 3*a* and 4*a*), has interesting consequences which we will discuss in § V.

The burst characteristics can also be expressed in terms of alpha values (Figs. 3*g* and 4*c*). Alpha values for individual bursts are represented by the inverse slopes of the data points in Figure 4*a* (alpha = E_p/E_b). For the majority of the bursts (with intervals less than 6 hr), the alpha values fall between 45 and 185; for the three strongest bursts (bursts 11, 26, and 27), with intervals in excess of 8 hr, all showing radius expansion, alpha ranges from 160 to 340 (Figs. 3*g* and 4*c*; see also Table 1).

The fluxes and fluences, given in Table 1, do not necessarily represent luminosities and energies through the usual geometric dilution factor ($4\pi d^2$) since both the burst emission and the persistent emission are probably anisotropic. For a particular thin disk geometry, Lapidus and Sunyaev (1985) have reported anisotropy factors for bursts of 1.4 (for 0° inclination), and 0.5 (for 90° inclination); for the persistent emission, these factors

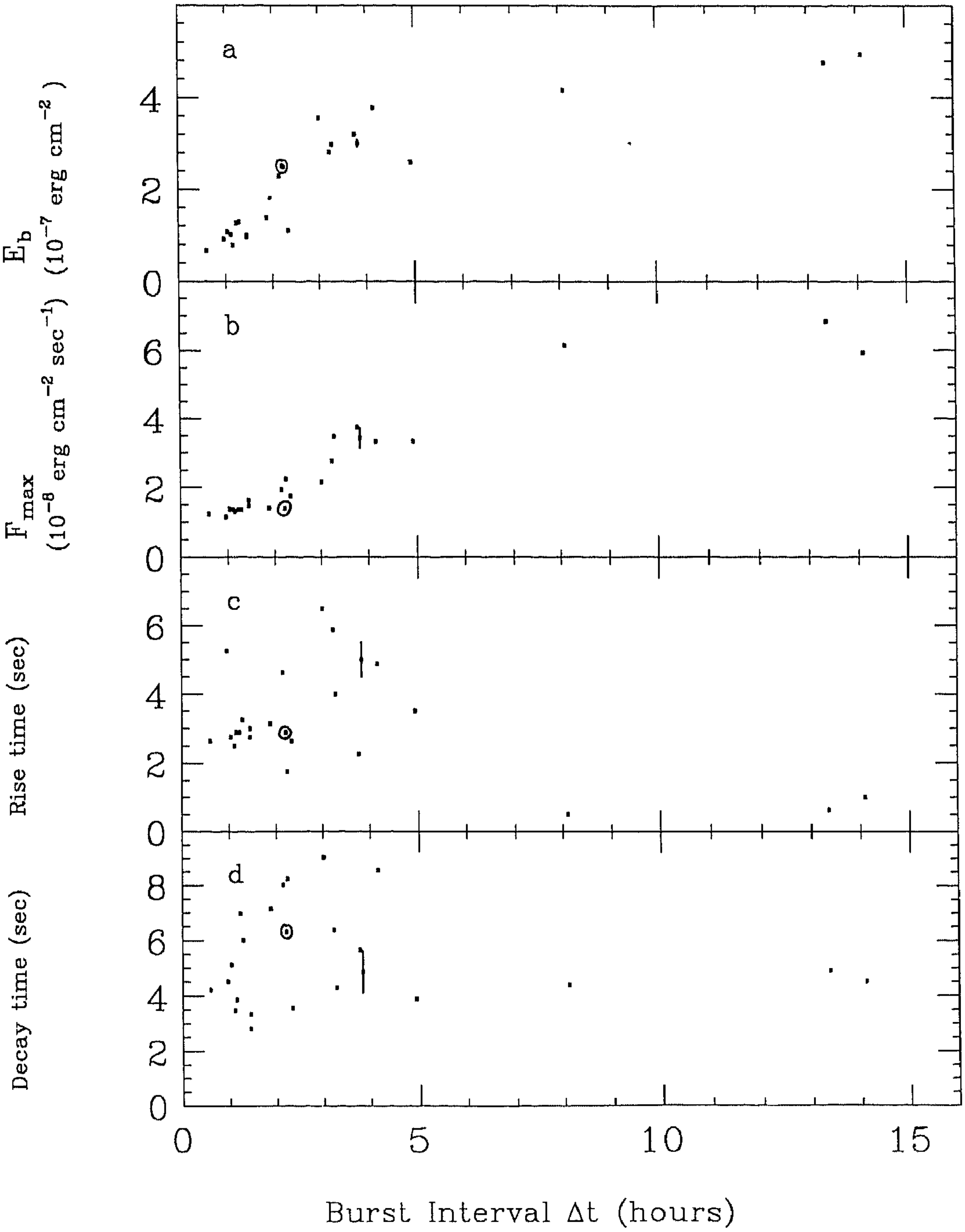

FIG. 3.—Burst and persistent emission properties plotted vs. the burst intervals Δt (in hr) since the preceding burst. Typical error bars are shown (for more information on uncertainties, see footnotes to Table 1). (*a*) Burst fluences E_b; (*b*) burst peak fluxes (F_{max}); (*c*) burst rise times (τ_r); (*d*) burst decay times (τ_d); (*e*) mean persistent bolometric fluxes (F_p) during the burst intervals Δt; (*f*) integrated bolometric persistent fluxes (E_p) during the intervals Δt; (*g*) alpha ($= E_p/E_b$; see text). Data for the triple-peaked burst (which is burst 25 in the table) (Van Paradijs *et al.* 1986), are encircled.

are 0.4 and 1.2, respectively. They thus predict that for systems with large inclination the anisotropy would suppress the bursts but would enhance the persistent emission. This would result in too large alpha values by a factor of about 2. Contrary to this prediction, in the eclipsing binary 0748−676 the observed alpha values are low (at least 11 or 22 bursts have alpha values less than 35). Clearly our understanding of the anisotropies is very incomplete.

It is interesting to mention here that the unknown burst anisotropy in 1636−53 does not change significantly on time scales up to several years. This follows from the fact that the observed distributions in values of F_{max} (including the gap), are the same, within the reported uncertainties, for observations taken years apart by three different observatories (Fujimoto *et al.* 1986). It is particularly striking that the peak fluxes in all bursts which caused photospheric radius expansion (they lie just above the gap), were very close to 6×10^{-8} ergs cm^{-2} s^{-1}.

If the degree of anisotropy does not change appreciably on

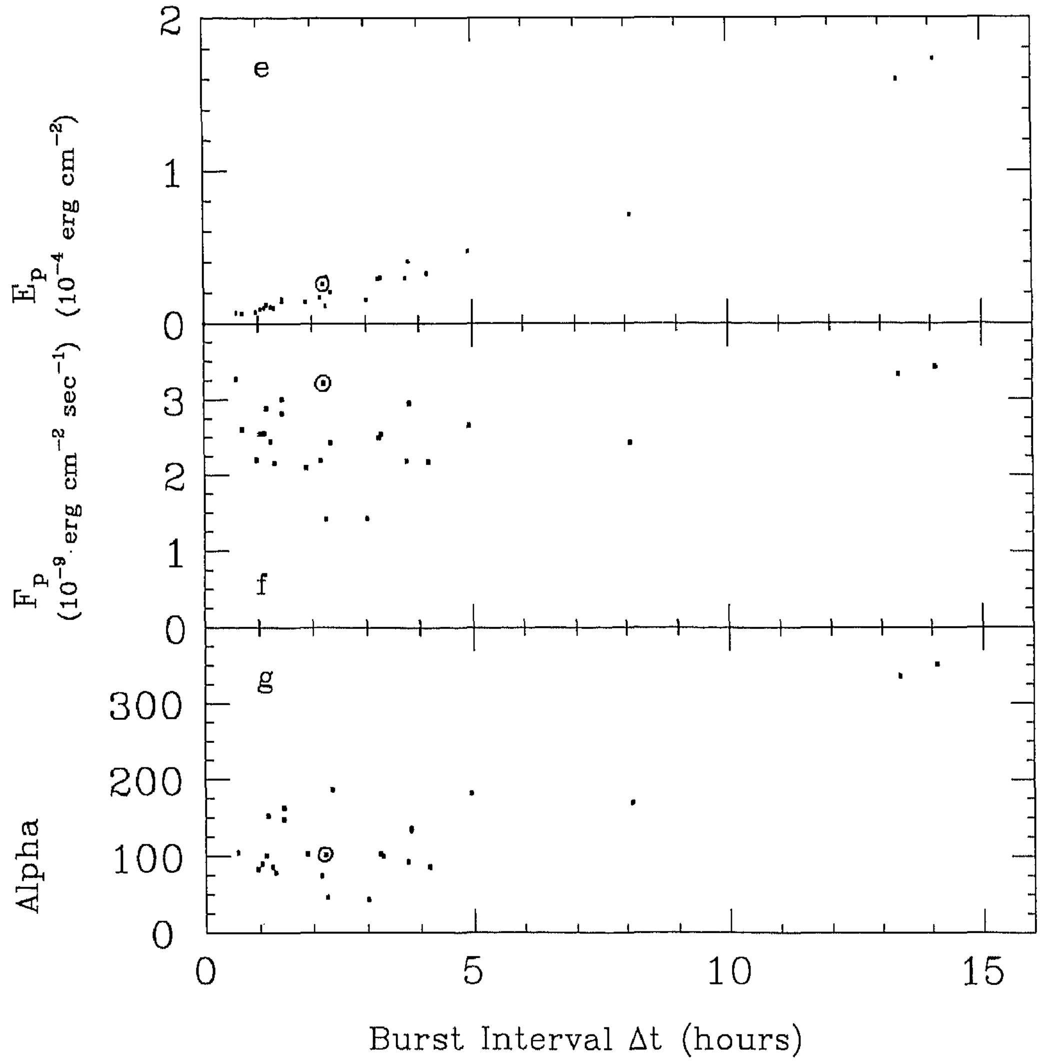

FIG. 3.—*Continued*

the time scales involved, the relative values, of E_b, F_{max}, F_p, and E_p separately have meaning independent of a possible difference in anisotropy between the persistent emission and the bursts. If by chance the anisotropy in the bursts and the persistent emission were approximately the same, the alpha values would not be affected.

For the majority of the bursts, the rise times are independent of the burst intervals; they scatter between about 2 and 6 s (Fig. 3*c*). However, the three strongest bursts (11, 26, and 27) (with radius expansion) all have rise times ≤ 1 s. Also, in 1820−30, and 0748−676 do bursts that cause radius expansion have relatively short rise times of about 1–2 s. The rise times in 1636−53 are not correlated in an obvious way with either the decay times or the persistent flux levels; excluding the above three bursts, there is no correlation with alpha either. Our results for 1636−53 are similar to those for 0748−676 (Gottwald *et al.* 1986).

The $1/e$ decay time (τ_d) range from about 3 to 12 s (Table 1) and are not correlated in an obvious way with either the burst intervals (Fig. 3*d*), the rise times, the burst energies, or the peak burst fluxes. There is some evidence that they may be correlated with the persistent flux (the higher the persistent flux, the shorter is the decay time), and with alpha (the higher alpha, the lower is the decay time).

We have explored the possibility that the $1/e$ decay times of bursts from 1636−53 may not properly reflect the possible presence of weak, but long, tails of 1–2 minutes (see Paper II). Therefore, we have independently calculated the times (τ_{d5}) for the bursts to decay from their peak values of 5% of these values. For 23 bursts τ_{d5} ranges from 15 to 28 s (among them are bursts 11, 26, and 27 with radius expansion). For burst 1, 2, and 25 (burst 25 is triple-peaked; Van Paradijs *et al.* 1986), the values are 44 s, 36 s, and 36 s, respectively. We found an empirical relation:

$$\tau_{d5} = 2.5 \times \tau_d + 8 \text{ s}$$

which holds to better than 10% for all bursts except bursts 1, 2, and 25. We find no evidence in our data for long burst tails in the 1–2 minute range (see Paper II).

In 1728−34 there was some evidence that periods of relatively low burst activity (i.e., long burst intervals), were associated with low values of the persistent flux (Basinska *et al.* 1984). Although the two very long intervals (13–14 hr) were observed near the end of our observations when the persistent flux was

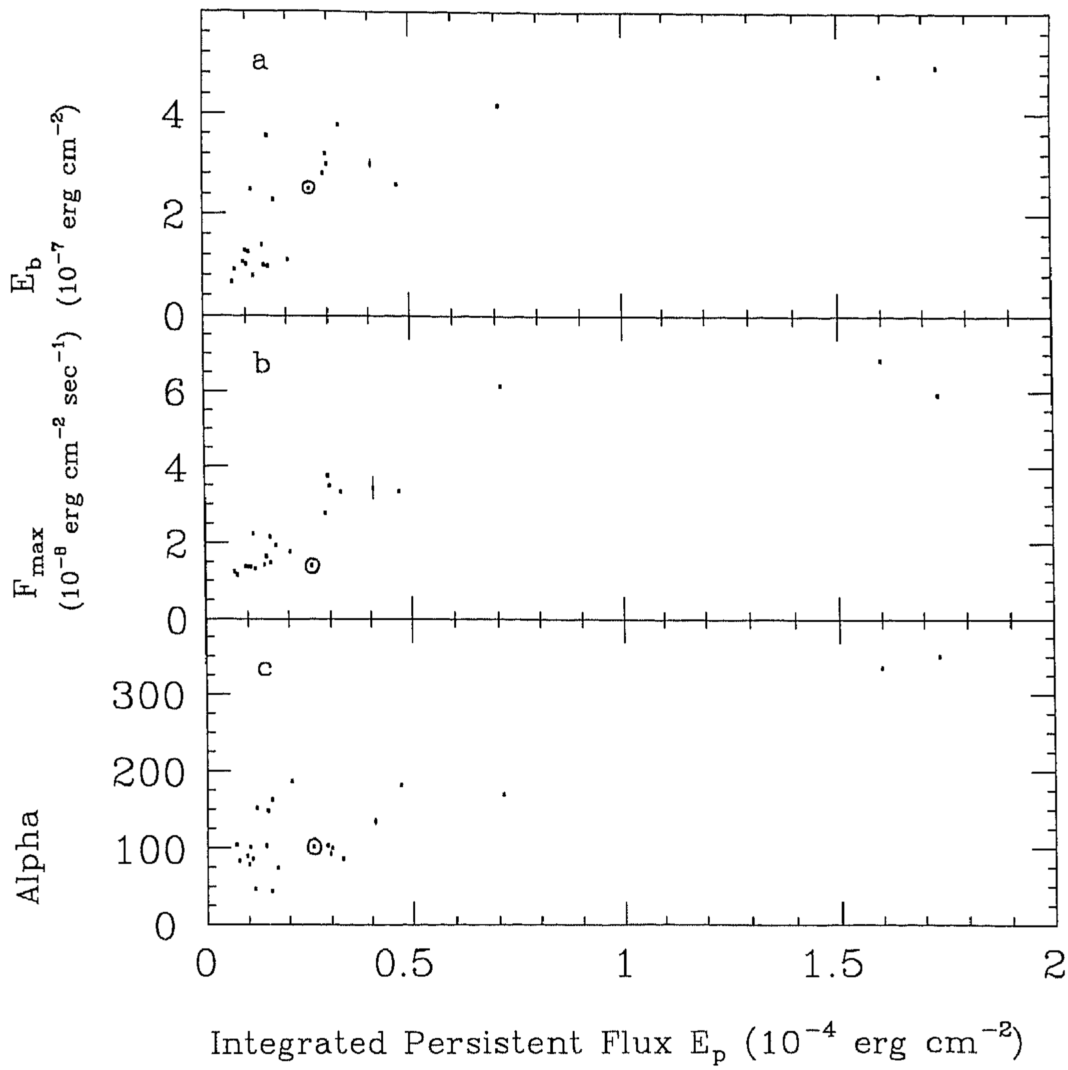

FIG. 4.—Burst properties vs. the integrated bolometric persistent fluxes (E_p) during the burst intervals (Δt). Typical error bars are shown (for more information on uncertainties, see Table 1). (*a*) Burst fluences E_b; (*b*) burst peak fluxes (F_{max}); (*c*) alpha ($= E_p/E_b$). Data for the triple-peaked burst (which is burst 25 in the table) (Van Paradijs *et al.* 1986), are encircled.

the highest (Fig. 1), our data for 1636−53 do not show a correlation between F_p and Δt (Fig. 3*e*). In 0748−676 the average burst intervals are clearly longer for higher persistent flux levels; the two are roughly proportional (Gottwald *et al.* 1986).

V. CONCLUSIONS AND IMPLICATIONS FOR THERMONUCLEAR FLASH MODELS

Globally speaking, putting aside for now the all-important deviations from linearity in individual bursts (we will return to this below), the correlation between E_b and Δt (Fig. 3*a*) suggests that the burst mechanism behaves somewhat like that of a filling water tank in which the amount of water that can be released depends roughly linearly on the time since the previous flushing. However, the proportionality of E_b and Δt (or E_p; Fig. 4*a*) clearly does not extend to the two bursts with the longest observed intervals of about 14 hr. A similar deviation from linearity has been found by Gottwalt *et al.* (1986) for 0748−676. Since both bursts (bursts 26 and 27 in Table 1) caused radius expansion, this can perhaps be explained in terms of the energy consumed in mass ejection (see e.g., Ebisuzaki, Hanawa, and Sugimoto 1983; Kato 1983; Quinn and Paczyński 1985; Paczyński and Anderson 1986; Paczyński and Proszynski 1986; Joss and Melia 1987). If $\frac{2}{3}$ of the thermonuclear energy was consumed in mass ejection, the approximate linear relation would hold over the whole range of observed intervals if the burst fluences are corrected for this loss of energy. We know from the work by Ebisuzaki, Hanawa, and Sugimoto (1983), and Kato (1983) that such large losses cannot be excluded.

If mass ejection cannot account for the lost energy, the above parallel could again be of some help. For waiting times longer than the "filling time," the amount of available water remains constant. Our data are well represented by a flush mechanism with a "filling time" of about 6 hr (Fig. 3*a*). In the context of continuous accretion, we can think of a water tank which is filled at a more or less constant rate and which overflows once it is full. The water that runs over is lost and will not be released when the tank is emptied.

The burst behavior could equally well be described by a reservoir which does not overflow but which has a leak (a sink) which is increasing in time as the burst intervals become longer.

The growing leak will cause the slope $E_b/\Delta t$ in Figure 3*a* (and E_b/E_p in Fig. 4*a*) to decrease gradually for increasing burst intervals. The leak cannot be constant as this would give a linear relation. This picture is also consistent with our data.

In the context of the thermonuclear shell flash models for bursts, it seems appropriate to adopt the latter picture whereby during the burst intervals there is a growing leak of nuclear energy (the percentage of lost energy is higher when the interval is longer).

Leakage of nuclear energy, which is then not released during the bursts, is also very evident from previous observations of 1735−44 (Lewin *et al.* 1980), and Ser X-1 (Sztajno *et al.* 1983) which have burst-active and burst-inactive periods with time scales of order of 1 day.

It has always been assumed (see e.g., Lewin *et al.* 1980; Sztajno *et al.* 1983) that these sources have extended periods in which nuclear burning occurs without becoming unstable, thus without a nuclear flash. In both Ser X-1 and 1735−44 the ratio of the mean persistent flux and the mean peak burst flux is about 5–10 times higher than for most other burst sources (Van Paradijs *et al.* 1979). This may indicate that the luminosities, and thus the accretion rates, are relatively high. The irregular burst behavior of these two sources may therefore be a "threshold" (in accretion rate) effect (Van Paradijs *et al.* 1979). For very high accretion rates such as, e.g., in 1820−30 in its high state, and GX 3+1 in its high state, no bursts are observed (for a review see, e.g., Lewin and Joss 1983).

For 1636−53 it may be possible to explain the energy leak simply in terms of continuous stable hydrogen burning through the CNO cycle. This produces a sink (the energy in a burst is largely due to hydrogen, and hydrogen burns to helium) which is growing in time as the production of helium per gram is roughly proportional with time. This possibility is worked out quantitatively in some details in Paper II. We emphasize, however, that this explanation may work for 1636−53 but cannot be the whole story for 1735−44 and Ser X-1 (see above).

The occurrence of burst intervals shorter than about 10 minutes has been a longstanding problem in itself (for a review see, e.g., Lewin and Joss 1983; see also Lewin 1985, and Gottwald *et al.* 1986). In 1636−53 the shortest interval was 6 minutes (Pedersen *et al.* 1982). It is clear from these very short intervals that a fair amount of nuclear fuel can survive a thermonuclear flash, as the accretion during these intervals is much too small to account for the observed bursts. It is not sufficient, however, that almost pure hydrogen survives (see e.g., Ayasli and Joss 1982; Woosley and Weaver 1984), since this cannot be ignited in the absence of helium and CNO nuclei (see also Paper II).

A fair amount of ignitable fuel (thus not pure hydrogen), representing an amount of energy of a medium size burst of order 10^{-7} ergs cm^{-2} for 1636−53 (see Fig. 3*a*), must often survive a thermonuclear flash.

A specific mechanism proposed by Fujimoto *et al.* (1986*b*) in the following paper can provide a semi-quantitative explanation for the scatter and the global burst behavior in our data of 1636−53 (Figs. 3*a* and 4*a*). This mechanism may also make an important contribution to our understanding of the very short (e.g., less than 10 minutes) burst intervals observed in 1636−53 (Pedersen *et al.* 1982) and several other sources (for reviews see Lewin 1984, 1985). What we would like to see, however (and who would not?), are model calculations (computer simulations) which reproduce (even if crudely) the observed burst sequences and characteristics as reported here for 1636−53.

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Note added in manuscript (1987 January 29).—Melia (1987) suggests that the triple-peaked burst (Van Paradijs *et al.* 1986; burst 25 in Table 1) may be the result of obscuration by, and scattering off, an accretion disk corona which comes into existence because of the burst. According to Melia (1987), the *observed* values for the burst fluence E_b and F_{max} for such a burst would then have to be substantially (∼3 times) smaller than what it would have been in the absence of such an accretion disk corona. The observed value for F_{max} for the triple-peaked burst is indeed rather low for the associated value of E_p (see circle, Fig. 4*b*); however, the value for E_b (Fig. 4*a*) is not at all low; we therefore doubt that Melia's model is applicable. We will discuss this further in a separate paper (Penninx, Lewin, and Van Paradijs 1987).

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