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TIME LAGS IN THE QUASI-PERIODIC OSCILLATIONS OF THE RAPID BURSTER (MXB 1730−335)

L. STELLA,[1, 2] F. HABERL,[1] W. H. G. LEWIN,[3] A. N. PARMAR,[1] M. VAN DER KLIS,[1] AND J. VAN PARADIJS[4]

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ABSTRACT

Based on two *EXOSAT* observations we present a study of time lags in the 0.4–5 Hz quasi-periodic oscillations (QPO) of the Rapid Burster. Different QPO modes occurred during long type 2 bursts (0.5–11 minutes) and in the persistent emission. The low-energy (1–5 keV) X-ray signal lagged the high-energy (5–21 keV) one by 7.6 ± 2.1 ms in the persistent emission QPO with frequencies >3.6 Hz. No significant time lag was detected in the QPO during bursts and in the 0.4–3.6 Hz QPO during persistent emission intervals; in the case of the >3.6 Hz QPO during bursts we can exclude an ∼8 ms lag of the low-energy X-ray QPO signal. The fractional strength of the QPO increased with photon energy during the persistent emission intervals.

These results provide the first evidence for a "soft" lag in QPO. If it is caused by direct Comptonization in a cold electron cloud, models where the QPO are produced by the oscillating optical depth can be ruled out. The soft lag might result from a spectral softening during each QPO cycle.

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

I. INTRODUCTION

The phenomenology of the quasi-periodic oscillations (QPO) which occur in bright low-mass X-ray binaries (for reviews see van der Klis 1986; Stella 1988) is complex and their origin unclear. The variety of QPO behavior in different sources and in different states of the same source has been used to place constraints on proposed QPO models (for reviews see Lewin 1987; Lamb 1988).

An additional tool has recently become available to investigate the physical process responsible for the QPO. A ∼2 ms and a ∼0.5 ms delay in the hard X-ray (5–18 keV) variations with respect to the soft (1–5 keV) ones ("hard" lag) have been found in the 20–40 Hz QPO of Cyg X-2 (Hasinger 1987) and GX 5-1 (van der Klis *et al.* 1987), respectively. These results have been interpreted in terms of inverse Comptonization of primary photons by a hot cloud surrounding the X-ray source (Hasinger 1987): on average hard photons escaping from the cloud have undergone more scatterings than soft photons and are, therefore, delayed (see also Stollman *et al.* 1987; Wijers, van Paradijs, and Lewin 1987; Bussard *et al.* 1988).

The Rapid Burster (MXB 1730−335), in addition to its unique burst properties (cf. Lewin and Joss 1983 and references therein), has been recently discovered to display different QPO modes in long (≥1 minute) type 2 bursts and the persistent emission between them (Stella *et al.* 1988*a*; see also Tawara *et al.* 1982). We present here a study of the time lags between soft and hard X-ray variations in the QPO of the Rapid Burster.

II. ANALYSIS AND RESULTS

The observations (see Table 1) were made with the medium energy instrument (ME) on board the European X-ray Observatory *EXOSAT* (Turner, Smith, and Zimmermann 1981). Energy-resolved data from the ME argon chambers were collected with a time resolution between ∼94 and ∼312 ms during the first observation and between ∼3.9 and ∼7.8 ms during the second observation. Light curves were obtained from these data in the 0.9–4.9 keV and 4.9–20.6 keV bands for the first observation, and in the 0.9–5.5 keV and 5.5–20.6 keV bands (rebinned to ∼31 ms) for the second observation.

During the first observation the source emitted ∼2.4 type 2 bursts per hour, at intervals ranging from ∼7 to ∼60 minutes. The bursts lasted from ∼1.3 to ∼11 minutes and had peak luminosities between $\sim 1.3 \times 10^{38}$ and $\sim 4 \times 10^{38}$ ergs s^{-1} (1–20 keV for a distance of 10 kpc). The highest peak luminosities were associated with the shortest bursts. Persistent emission between bursts, at an average level of $\sim 2.6 \times 10^{37}$ ergs s^{-1}, was observed which varied typically by a factor of ∼2 between two consecutive bursts (see Stella *et al.* 1988*a*). QPO were detected in more than half of the bursts and in 14 out of 16 bursts longer than 3 minutes; average QPO frequency during a burst varied between 2 and 5 Hz and was anticorrelated with burst luminosity. QPO were also observed occasionally in the persistent emission after relatively short (1–2 minute) bursts. In these cases the QPO frequency evolved from ∼4 Hz after a burst to ∼2 Hz in 3–6 minutes (see Figs. 1 and 2 in Stella *et al.* 1988*a*) and was positively correlated with spectral hardness, while there was no general correlation with luminosity. QPO with frequencies between 0.4 and 1 Hz were also observed occasionally during intervals of 1–2 minutes before bursts.

During the second observation the burst rate increased to ~ 4.3 hr^{-1}, the burst durations ranged from ∼0.5 to ∼3 minutes (only two bursts were longer than 3 minutes), while the burst peak luminosity varied from $\sim 1.3 \times 10^{38}$ to $\sim 4 \times 10^{38}$ ergs s^{-1} (Stella *et al.* 1988*b*). The QPO behavior was similar to that during the first observation, except that no QPO were detected with frequencies less than ∼2 Hz. Figure 1 (Plate L1) shows an interval of data obtained during the second observation. During both observations the 1–15 keV rms fractional variation of the QPO reached values as high as ∼20% and ∼35% in the bursts and the persistent emission, respectively.

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[1] EXOSAT Observatory, Astrophysics Division, Space Science Department, European Space Agency, ESTEC, The Netherlands.

[2] On leave from I.C.R.A., Department of Physics "G. Marconi," University of Rome, Italy.

[3] Massachusetts Institute of Technology, Center for Space Research and Physics Department.

[4] Astronomical Institute "Anton Pannekoek," University of Amsterdam.

TABLE 1

AVERAGE TIME LAGS IN THE QPO OF THE RAPID BURSTER

TIME OF OBSERVATION (UT)	ν_{QPO} (Hz)	BURSTS ν-Range (Hz)	BURSTS Hard Lag (ms)	PERSISTENT EMISSION ν-Range (Hz)	PERSISTENT EMISSION Hard Lag (ms)
1985 Aug 28–29 (15:30–8:30)	>3.6	3.5–5.3	$+0.4 \pm 0.8$	3.3–4.6	-7.7 ± 6.4
	<3.6	1.9–2.5	-12 ± 12	2.5–3.2	-2.7 ± 3.6
				0.4–1.0	-23 ± 25
1985 Aug 30–31 (18:30–7:30)	>3.6	...	...	3.3–4.6	-7.6 ± 2.2
	<3.6	1.9–2.5	-4.3 ± 3.9	2.5–4.3	-3.4 ± 2.2

The QPO time lags were investigated by using a cross-spectrum analysis technique (cf. van der Klis *et al.* 1987). The light curves were divided into consecutive intervals of 256 time bins and the cross spectrum calculated for each of them. The cross spectra from the intervals showing 2–5 Hz QPO were averaged into four different groups defined by the QPO centroid frequency being smaller or larger than 3.6 Hz[5] and by the source being in the burst or the persistent emission regime. This was done independently for each of the two observations. The average cross spectrum was also calculated for those intervals of the first observation during which low-frequency QPO (0.4–1 Hz) were detected.

During the first ~8 hr of the first observation the Nyquist frequency was in several instances comparable to, or even smaller than, the measured QPO frequency (see Stella *et al.* 1988*a*). In the second observation, QPO with frequencies higher than 3.6 Hz during bursts were detected only marginally, such that the cross spectrum did not provide any useful results. Corrections for dead-time–induced cross talk between the two energy bands were carried out following van der Klis *et al.* (1987). None of the results presented here depend significantly on the details of these corrections.

Figure 2 shows some of the cross spectra obtained from the two observations. The complex cross spectral amplitudes are plotted as vectors, with the real parts (cospectrum) along the Y-axis and the imaginary parts (quadrature spectrum) along the X-axis. The frequency axis is plotted along the diagonal line (van der Klis *et al.* 1987). In this representation the phase lag in each frequency bin is measured by the angle between the vector and the Y-axis. Vectors leaning to the left indicate a "hard" phase lag, while vectors leaning to the right indicate a "soft" phase lag. The errors in the real and imaginary parts in each frequency bin were evaluated directly from the scatter around the mean values in the process of averaging individual cross spectra.

The length of the vectors as a function of frequency clearly reveals the presence of the QPO peak in the cross spectra of Figure 2. The average time lags for the QPO were obtained by averaging the phase lags of the vectors in the QPO peak. The results are given in Table 1 (positive values correspond to hard lags).

During the first observation no significant time lags were detected. Due to the high incidence of >2 minute long type 2 bursts, strict limits of +1.7 ms and −0.9 ms (90% confidence) could be set on any hard lag in the >3.6 Hz QPO during bursts. Less tight constraints were derived for the <3.6 Hz QPO during bursts and the ~0.4–5 Hz QPO in the persistent emission (Table 1).

During the second observation a soft lag of -7.6 ± 2.2 ms was revealed for the QPO with frequencies >3.6 Hz observed in the persistent emission. The significance of this result is ~3.5 σ; when combined with the corresponding result from the first observation (-7.7 ± 6.4 ms) the significance increases to ~3.7 σ. It is important to realize that all other values reported in Table 1 are consistent with this soft lag; the only exception is the time lag ($+0.4 \pm 0.8$ ms) for the >3.6 Hz QPO during bursts, which is inconsistent with it (>99.97% confidence). The analysis of the second observation was repeated with energy boundaries of 0.9–3.4 keV and 3.4–10 keV. The time lags obtained were consistent with those reported in Table 1. Due to the weakness of the red noise (RN) in the power spectra of the Rapid Burster (cf. Stella *et al.* 1988*a*), no useful information could be obtained on the time lags for frequencies <0.4 Hz.

In order to investigate also the dependence of QPO strength on photon energy, average power spectra were accumulated in three different energy bands, according to the criteria used for the cross spectra. The rms fractional variation, ϵ, of the QPO (corrected for channel cross talk) was then evaluated. The results are shown in Figure 3. During the bursts, ϵ showed a marginal increase with energy and the hypothesis of constancy could be rejected only with 90% confidence (χ^2/dof = 9.1/5). In the persistent emission, ϵ was inconsistent with being independent of energy (χ^2/dof = 23.7/5) and a significant slope of $(2.4 \pm 0.5)\%$ keV^{-1} was measured. QPO frequency changes did not produce any significant change in the strength of the QPO as a function of energy, both during the bursts and in the persistent emission.

III. DISCUSSION

We detected an ~8 ms soft lag in the >3.6 Hz persistent emission QPO of the Rapid Burster. This result constitutes the first example of QPO in which the low-energy X-rays lag those at high energies. By contrast, the >3.6 Hz QPO during long type 2 bursts did not show any time lag between soft and hard X-rays with an upper limit of ~2 ms. The upper limits on the time lags in the <3.6 Hz QPO during bursts or in the persistent emission intervals were not sufficiently tight to exclude an ~8 ms soft lag.

If the Compton effect is invoked to explain the QPO time lags, as in the case of the 20–40 Hz QPO from Cyg X-2 and GX 5-1 (Hasinger 1987; van der Klis *et al.* 1987), then the sign of the lag in the Rapid Burster requires a Comptonizing cloud with an average electron energy lower than the energy of the primary photons. According to the Monte Carlo simulations carried out by Stollman *et al.* (1987), a time lag of ~8 ms implies a size of a few times 10^8 cm for a Comptonizing cloud

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[5] Figure 2*a* in Stella *et al.* (1988*a*) shows that the QPO during bursts divide naturally into two groups with frequencies of ~2–3 Hz and ~4–5 Hz.

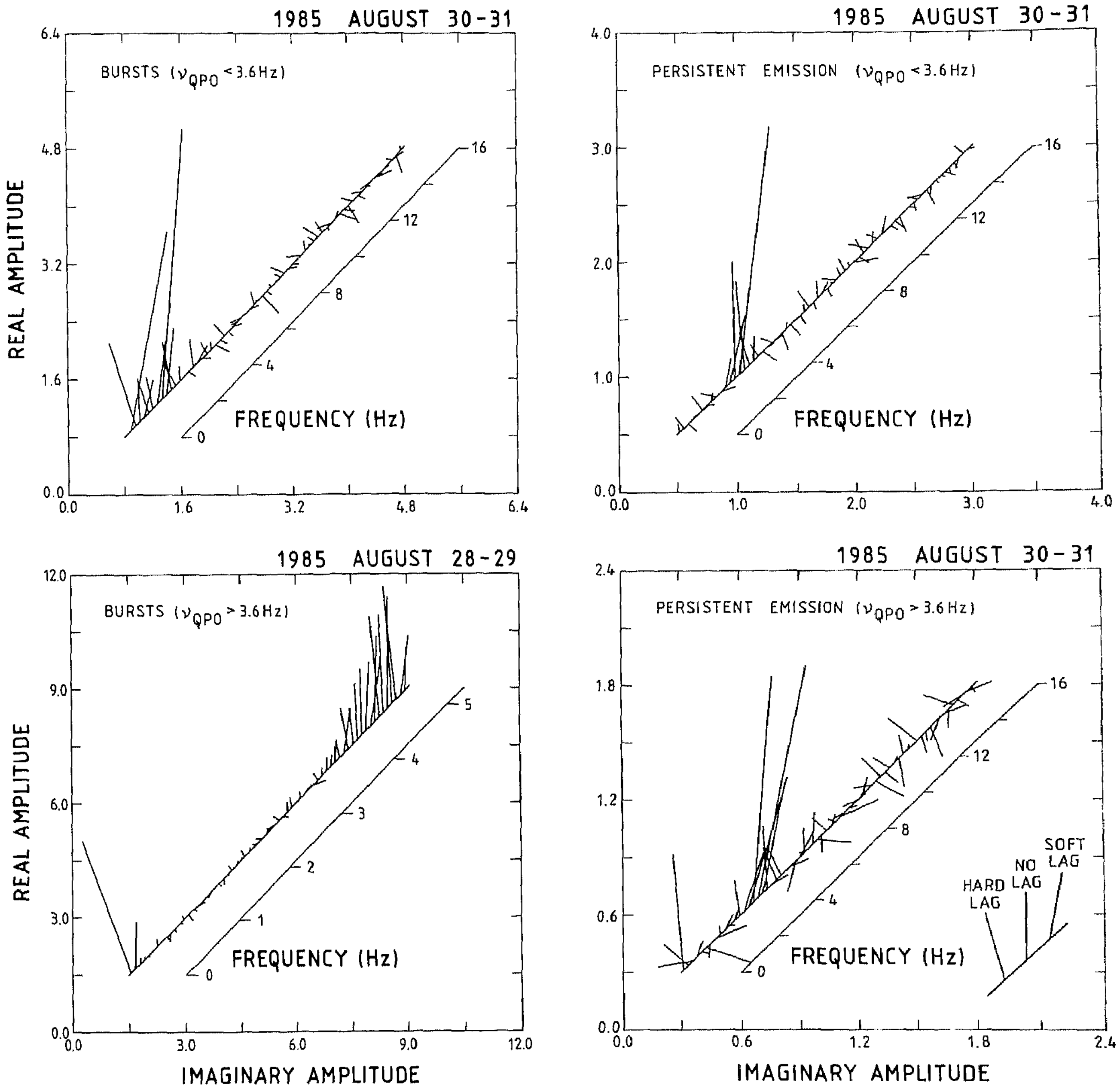

FIG. 2.—Average complex cross spectra in the four data sets described in the text. The diagonal line represents the frequency axis. The complex amplitudes are plotted as vectors in 64 independent frequency bins. Vectors leaning right (left) with respect to the vertical axis indicate a soft (hard) time lag. Here and in Fig. 3 the data are from the 1985 August 30–31 observation, except for the data on the >3.6 Hz QPO during bursts which are from the 1985 August 28–29 observation. The >3.6 Hz QPO in the persistent emission show a significant ~8 ms soft lag.

with τ ~10. The decrease of the soft lag to <2 ms in the >3.6 Hz QPO during long type 2 bursts then implies changes in the properties of the Comptonizing cloud and/or the primary photons. Possibly, the optical depth of the cloud increased during intervals of persistent emission, causing a more efficient downscattering of the photons, and a larger soft lag. The fact that the source spectrum was considerably softer in the persistent emission than in the type 2 bursts (see Stella *et al.* 1988*a*) supports this view.

In principle a QPO signal with time lags between different energy bands can either be generated by an oscillating source of primary photons in a constant cloud, or by Comptonization of a constant source in a cloud with an oscillating optical depth (Stollman *et al.* 1987). In the latter case the fractional strength of the QPO as a function of energy, $\epsilon(E)$, depends mainly on the properties of the Comptonizing cloud, with $d\epsilon/dE > 0$ in the case of a hot cloud and $d\epsilon/dE < 0$ in the case of a cold cloud. The fact that $d\epsilon/dE > 0$ in the persistent emission QPO from the Rapid Burster, when a soft lag was measured, then argues against models involving a cloud with oscillating optical depth.

The soft lag in the QPO of the Rapid Burster occurs in the same low-frequency range as the soft lag seen in the ~1–10 Hz RN during the horizontal branch spectral state of Cyg X-2 and GX 5-1 (van der Klis *et al.* 1987). The hard lags seen in these two sources occur at the much higher frequencies (~20–40 Hz)

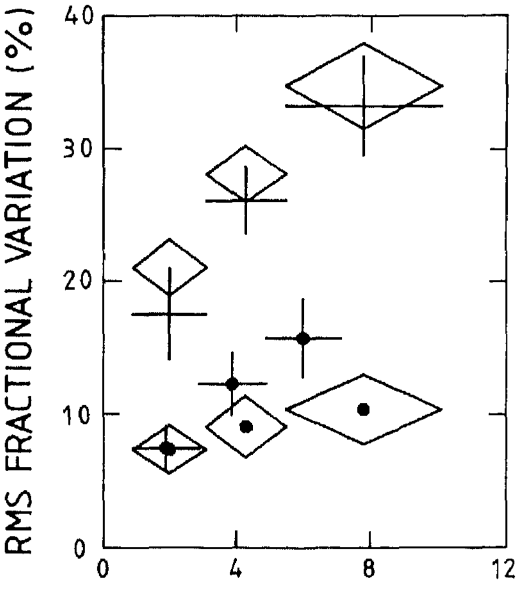

FIG. 3.—QPO rms fractional variation as a function of energy in the four data sets described in the text. Crosses refer to > 3.6 Hz QPO and diamonds to < 3.6 Hz QPO. Solid dots mark the values obtained during type 2 bursts; the others are for the persistent emission.

of the horizontal-branch QPO. One might therefore conjecture that whether a soft or a hard lag is seen depends only on the time scale of the intensity variations. The recent detection with the X-ray satellite *Ginga* of a ~70 ms hard lag in the ~5 Hz normal-branch QPOs of Cyg X-2 (Mitsuda 1988) argues against this interpretation.

If the X-ray signal is described in terms of oscillating shots (with the "envelope" of the shots causing the RN and the oscillations in the shots causing the QPO; cf. Shibazaki and Lamb 1987) then a spectral softening in the shot can produce a frequency-dependent soft lag dominating any hard lag caused by Comptonization in a hot cloud. If the soft lags are produced by a softening of the shots, a considerable amount of RN is usually produced, while the soft lags are larger at low frequencies, as observed in GX 5-1 and Cyg X-2.

For the Rapid Burster, the soft lag at the QPO frequencies, together with the near absence of RN and the relatively high coherence of the QPO (implying that there are up to ~6–7 QPO cycles per shot; cf. Stella *et al.* 1988*a*) suggest that the spectral softening occurs in the course of every individual oscillation cycle and on time scales considerably shorter than the shot envelope. In this scenario the QPO signal in the shots could not be purely sinusoidal, and harmonics to the main QPO peak would be expected, as is indeed observed (at least in some instances; Stella *et al.* 1988*a*); the fact that the ~8 ms soft lag in the > 3.6 Hz persistent emission QPO decreased to < 2 ms in the > 3.6 Hz QPO during long type 2 bursts requires a change in the softening properties of the oscillations. It remains to be seen whether the degree of asymmetry needed in the QPO signal to explain the soft lags by such a mechanism can be reconciled with the level at which harmonics to the main QPO peak are detected in the data.

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REFERENCES

Bussard, R. W., Weisskopf, M. C., Elsner, R. F., and Shibazaki, N. 1988, *Ap. J.*, in press.
Hasinger, G. 1987, in *IAU Symposium 125, The Origin and Evolution of Neutron Stars*, ed. D. J. Helfand and J. H. Huang (Dordrecht: Reidel), p. 333.
Lamb, F. K. 1988, in *Proc. COSPAR-IAU Symposium, The Physics of Compact Objects: Theory versus Observations*, ed. N. E. White and L. Filipov (Oxford: Pergamon), in press.
Lewin, W. H. G. 1987, in *IAU Symposium 125, The Origin and Evolution of Neutron Stars*, ed. D. J. Helfand and J. H. Huang (Dordrecht: Reidel), p. 363.
Lewin, W. H. G., and Joss, P. 1983, in *Accretion Driven Stellar X-Ray Sources*, ed. W.H.G. Lewin and E. P. J. van den Heuvel (Cambridge: Cambridge University Press), p. 43.
Mitsuda, K. 1988, in *Proc. COSPAR-IAU Symposium, The Physics of Compact Objects: Theory versus Observations*, ed. N.E. White and L. Filipov (Oxford: Pergamon), in press.
Shibazaki, N., and Lamb, F. K. 1987, *Ap. J.*, **318**, 767.
Stella, L. 1988, in *Proc. COSPAR-IAU Symposium, The Physics of Compact Objects: Theory versus Observations*, ed. N. E. White and L. Filipov (Oxford: Pergamon), in press.
Stella, L., Haberl, F., Lewin, W. H. G., Parmar, A. N., van Paradijs, J., and White, N. E. 1988*a*, *Ap. J.*, **324**, 379.
Stella, L., *et al.* 1988*b*, in preparation.
Stollman, G. M., Hasinger, G., Lewin, W. H. G., van der Klis, M., and van Paradijs, J. 1987, *M.N.R.A.S.*, **227**, 7P.
Tawara, Y., Hayakawa, S., Kunieda, H., Makino, F. and Nagase, F. 1982, *Nature*, **299**, 38.
Turner, M. J. L., Smith, A., and Zimmermann, H. U. 1981, *Space Sci Rev.*, **30**, 513.
van der Klis, M. 1986, in *The Physics of Accretion onto Compact Objects*, ed. K. O. Mason, M. G. Watson, and N. E. White (Berlin: Springer Verlag), p. 157.
van der Klis, M., Hasinger, G., Stella, L., Langmeier, A., van Paradijs, J., and Lewin, W. H. G. 1987, *Ap. J.* (*Letters*), **319**, L13.
Wijers, R. A. M. J., van Paradijs, J., and Lewin, W. H. G. 1987, *M.N.R.A.S.*, **228**, 17P.

F. HABERL, A. N. PARMAR, L. STELLA, and M. VAN DER KLIS: EXOSAT Observatory, Space Science Department of ESA, ESTEC, Postbus 299, 2200 AG Noordwijk, The Netherlands

W. H. G. LEWIN: Massachusetts Institute of Technology, Center for Space Research and Physics Department, Cambridge, MA 02139

J. VAN PARADIJS: Astronomical Institute "Anton Pannekoek," University of Amsterdam, Roetersstraat 15, 1018 WB Amsterdam, The Netherlands