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EXOSAT OBSERVATIONS OF THE LOW-LUMINOSITY X-RAY BURSTER 4U 0614+091: EVIDENCE FOR A HARD POWER-LAW TAIL

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ABSTRACT

We have analyzed archival *EXOSAT* observations of 4U 0614+091 as recorded by the Medium Energy experiment (2–10 keV). The data set consists of five spectra, all associated with low X-ray luminosities ($L_{(X,1-20\ \mathrm{keV})} \leq 2 \times 10^{36}$ ergs s^{-1}, $d = 2$ kpc). The spectrum corresponding to the highest intensity state ($F_X = 3.9 \times 10^{-9}$ ergs cm^{-2} s^{-1}) is well fitted by the combination of a steep power law with a photon index of 2.7 and a relatively strong 1.5 keV blackbody component carrying off 25% of the total 1–20 keV luminosity. The two spectra associated with the lowest X-ray fluxes ($F_X = 1.2$, 1.1×10^{-9} ergs cm^{-2} s^{-1}) are adequately described by the sum of a harder power law (photon index ∼1.9) and a cooler blackbody component (∼0.5 keV) carrying of 6% and 10% of the 1–20 keV flux, respectively. Finally, for the two other spectra with slightly larger X-ray fluxes ($F_X = 1.5 \times 10^{-9}$ ergs cm^{-2} s^{-1}), both are best fitted by a single power law (photon index ∼2.1–2.2), and an upper limit of ∼10% on the contribution of any blackbody component with temperature between 0.5 and 1.5 keV has been derived.

4U 0614+091 enlarges the list of X-ray bursters displaying a hard power-law spectrum in X-rays at low-luminosity states, as well as a clear anticorrelation between spectral hardness and intensity. The *EXOSAT* results show that when the contribution of the blackbody component reaches 25% of the total 1–20 keV flux, the spectrum steepens. This result strengthens the idea that the presence of a strong blackbody emission (most likely originating from the surface of the compact object) may be responsible for the quenching of the high-energy emission in high-luminosity neutron star systems. On the other hand, the same data show also that when the blackbody component contributes, less than ∼10%, it does not affect the high-energy emission of the system.

The *EXOSAT* results may also account for the fact that 4U 0614+091 was previously detected by *HEAO 1* A-4 up to 80 keV, when the source was probably in a very low state. Both the *HEAO 1* A-4 and *EXOSAT* results add support to the hypothesis that X-ray bursters emit low-flux, hard X-ray tails when they reach low-intensity states.

Subject headings: stars: individual (4U 0614+091) — X-rays: bursts — X-rays: stars

1. INTRODUCTION

X-ray bursters are low-mass X-ray binaries (LMXBs) where the compact object is a weakly magnetized neutron star. They have persistent X-ray luminosities with typical values L_x (1–20 keV) $\sim 10^{36}$–10^{37} ergs s^{-1} and are characterized by variations in their persistent emission by up to one order of magnitude. For those sources that have been observed at different intensity states in soft X-rays (defined here as below 20–30 keV), there is a common tendency for the spectrum to harden while the source luminosity (or at least the 2–20 keV flux) decreases. Mitsuda et al. (1989) observed 4U 1608−522 as it varied over a wide range of luminosity (6×10^{36}–3×10^{37} ergs s^{-1}, for an assumed distance of ∼3 kpc) and found that the spectral slope evolves from a thermal type to a power-law type as the source luminosity decreased. In some other cases when fitting the X-ray spectra by a combination of a power law and an exponential cutoff (an approximation of the Comptonization model), it is found that the power-law index decreases and the cutoff energy moves toward higher energies as the source intensity decreases (e.g., 4U 1735−444, Smale et al. 1986; 4U 1636−536, Breedon et al. 1986). Finally, there are some other sources which are always observed to have a power-law–type spectrum (e.g., 4U 1916−053, Smale et al. 1988), suggesting that they always remain in their low-intensity state. As a common property, all the power laws observed from these sources are characterized by photon index ∼2 in the 2–20 keV band (see Barret & Vedrenne 1994, and references therein).

In addition to these soft X-ray data, it is only recently that there exist some observations of X-ray bursters at hard X-ray energies (above 35 keV). These observations, provided mainly by the SIGMA telescope, have shown that X-ray bursters can also emit high-energy tails extending up to 100 keV (Barret & Vedrenne 1994). The four X-ray bursters detected so far by SIGMA (KS 1731−260, Barret et al. 1992; GX 354−0, Claret et al. 1994; X1724−308 in Terzan 2, Barret et al. 1991; and A1742−294, Churazov et al. 1995) are all characterized by steep, hard X-ray spectra (power-law photon index typically ∼3),[3] low, hard X-ray (35–200 keV) fluxes and luminosities (∼10^{37} ergs s^{-1}).

Although there is no simultaneous soft X-ray data for the SIGMA observations (all sources were outside the smaller field of view of the ART-P X-ray telescope at the time it was still operating), Barret & Vedrenne (1994) have hypothesized that the hard X-ray tails observed by SIGMA were likely to be associated with low-intensity states of the sources, when their 2–20 keV X-ray spectra would have a power-law shape. If this

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[3] Though in one set of observations, X1724−308 in Terzan 2 had a significantly flatter spectrum (see Barret et al. 1991).

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picture is correct, the X-ray and the SIGMA spectra suggest the existence of a spectral break or more likely a high-energy cutoff in a single power-law occurring somewhere in the hard X-ray range (between 30 and 100 keV). Such spectra extending from X-rays to hard X-rays could then be interpreted in terms of Comptonization of cool photons on hot electrons located somewhere in the system, most probably in an accretion disk corona. Furthermore, in the framework of a Comptonization process, the typical softness/intensity relationship observed could be explained as due to the Compton cooling of the hot corona, when the flux of soft photons (e.g., blackbody emission from the neutron star surface) rises in response to an increasing accretion rate (Sunyaev & Titarchuck 1989).

A test of the Barret & Vedrenne (1994) hypothesis is to check whether the low-luminosity bursters are all characterized by hard spectra in X-rays, which may eventually yield detectable hard X-ray fluxes. In the *EXOSAT* database, which currently represents the largest available data set for X-ray bursters, we have therefore selected 4U 0614+091: an intrinsically faint system. 4U 0614+091 is a LMXB optically identified with a faint blue star ($B \sim 18.8$) located in the Galactic plane (Davidsen et al. 1974). Its distance is unknown, but it has been estimated to be ∼4 kpc (Davidsen et al. 1974; Machin et al. 1991). Its X-ray luminosity ranges typically between 1 and 8×10^{36} ergs s^{-1} (2–10 keV). It was first suspected to be an X-ray burster by Swank et al. (1978). This was confirmed recently by the WATCH all-sky monitor on-board *Granat*, which observed a bright X-ray burst within $0\overset{\circ}{.}5$ around 4U 0614+091 (Brandt et al. 1992). The very high burst peak flux as observed by WATCH implies (for an Eddington limit in luminosity) that 4U 0614+091 is close—only ∼2 kpc—and thus indeed a low-luminosity system.

Previous soft X-ray observations of 4U 0614+091 have been reported by Christian, White, & Swank (1994) and Christian (1993) using *Einstein* MPC–SSS data, and by Smale et al. (1992) using BBXRT. Christian (1993) used a set of four combined MPC (1.2–20 keV) and SSS (0.5–4.5 keV) observations and fitted the data with a power law and an exponential cutoff. He found that while the source intensity increased by about a factor of 2 (the flux always lower than 2.7×10^{-9} ergs cm^{-2} s^{-1}, 0.5–20 keV), the spectral slope remained constant within confidence limits with a photon index of ∼2 and cutoff energy at ∼25 keV (note that this value is uncertain because it is above the upper end of the MPC energy range). Furthermore, Christian et al. (1994) found in the SSS data a low-energy emission line centered at 0.77 keV, which was interpreted as emission from an accretion disk corona excited by the central X-ray source. As far as the BBXRT data are concerned, the best fit was a single power law with index 2.58 (Smale et al. 1992), and the source was observed in a low-intensity state (Christian 1993). Clearly, all these X-ray observations indicate that 4U 0614+091 is an X-ray burster which spends a large amount of time in a hard state when its X-ray spectrum has a power-law shape.

Light-curve analysis of a simultaneous *EXOSAT* and optical observation on 4U 0614+091 was previously reported by Machin et al. (1991), but so far detailed spectra have not been presented. Here we present only the spectral analysis of the *EXOSAT* ME data. A more detailed paper on the timing analysis of the X-ray flux from 4U 0614+091 is in preparation (Callanan et al. 1995).

The paper is organized as follows. In § 2, we describe the data set consisting of five observations and report on the results of the spectral analysis. In § 3, we discuss the results in terms of hard X-ray emission from neutron star systems.

2. OBSERVATIONS AND RESULTS

The *EXOSAT* database contains a total of five ME spectra of 4U 0614+091. All the observations have quality flag greater than 4, indicating very good data. Table 1 lists the dates of the observations considered in this paper. Simultaneous optical data were recorded only for observation (*e*) (Machin et al. 1991).

2.1. *Light Curves*

For the first four observations, the ME experiment (Turner et al. 1981) was operating normally. The source was observed with one half-array, whereas the background was monitored simultaneously using the other one. For the last observation, to allow for systematic differences, the detector halves viewing the source and the background were alternated twice. Figures 1*a*–1*e* shows the background-subtracted light curve of the source between 1 and 8 keV. As can be seen, no X-ray bursts were observed by *EXOSAT* in any of the five observations. From observation c to observation e the count rate increased by a factor of ∼3. For the first four observations, the source flux was constant within the observation, while for the last one the source shows count rate variations by up to ∼50% on a half-day timescale (see Machin et al. 1991 for a discussion). The slight increase of the flux at the beginning of observations a and b is explained by the fact that the satellite was still moving toward the source and was not yet pointed directly at the source position.

2.2. *Spectral Analysis*

The spectra of observations a–d were acquired in 32 PHA channels, whereas for observation e the spectrum was recorded in 64 PHA channels. In the present paper, we consider only the argon data. The raw spectra have been fitted from ∼2 keV to an upper energy in the range 10–12 keV depending on the

TABLE 1

LOG LIST OF THE *EXOSAT*-ME OBSERVATIONS OF 4U 0614+091[a]

Observation Identification	Date	Start Time (UT)	Stop Time (UT)	Duration (hr)	Count Rate (counts s^{-1} half^{-1})
a.............	1984 Sep 28	08:04	11:58	3.87	65.7
b	1984 Oct 31	01:48	07:45	5.95	65.4
c.............	1984 Nov 5	01:30	04:49	3.33	54.0
d	1984 Nov 8–9	20:34	00:42	4.13	47.9
e.............	1986 Feb 12–13	22:40	13:50	14.47	179.2

[a] The averaged counting rates are given in the 1–8 keV band.

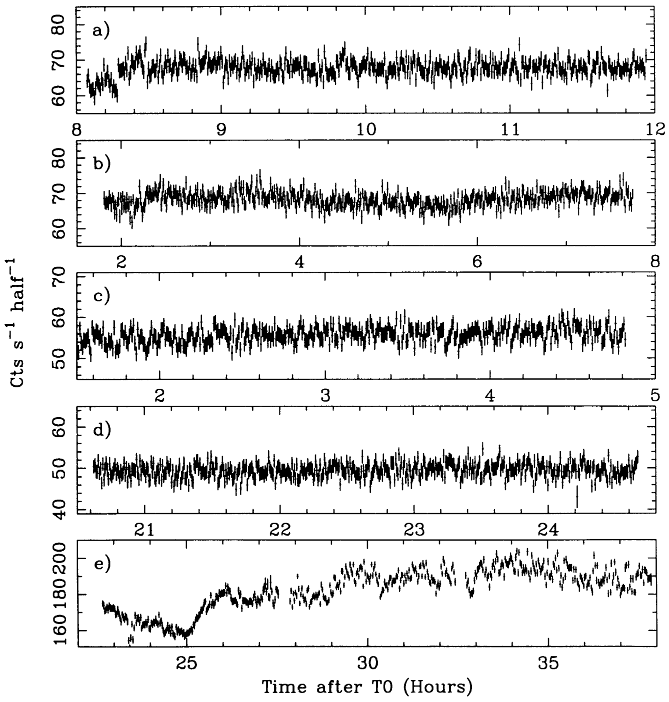

FIG. 1.—(a)–(e) 1–8 keV *EXOSAT* Me background-subtracted light curves of 4U 0614+091.

source brightness. The spectral analysis has been carried out using the XSPEC software package (Shafer et al. 1991).

In our analysis, we have first considered simple one-component models which have proved to be successful to account for the 2–10 keV spectra of X-ray bursters (see White, Stella, & Parmar 1988 for a discussion about models). These models are a power-law, a Comptonization model, and its approximation: a power-law and exponential cutoff. However, we note that the last two models, whose parameters (electron temperature and optical depth, and cutoff energy) can be reliably estimated when there is a cutoff in the spectrum, are meaningless when applied to power-law type spectra. Because blackbody-like emission has also been observed in the spectra of X-ray bursters (mainly in their high states; see for, example 4U 1705–44, Langmeier et al. 1987), we have also considered two-component models (e.g., power-law + blackbody, etc.).

2.3. *Spectra a, b*

These two spectra are well fitted by a single power law. Results of these fits are listed in Table 2, together with the associated unabsorbed X-ray flux in the 1–20 keV band. Given the quality of the fits ($\chi^2_\nu \leq 1.0$), the addition of a blackbody component is not justified. Because such a blackbody component is indeed observed in spectra c, d, e (see below), we have used the data to set an upper limit on the luminosity of a possible blackbody component. For a given blackbody temperature, this is done by increasing the blackbody contribution until the minimum χ^2 found during the fit becomes larger than a value for which the probability of getting higher χ^2 value is 10^{-2} (i.e., at 99% confidence level). Obviously, both the blackbody temperature and normalization factor at 1 keV are fixed during the fit. For 15 degrees of freedom, the χ^2 value to reach is 2.04. By applying this method, it appears that the evolution of the χ^2 is a smooth increasing function of the contribution of the blackbody component. By inspecting this curve, we have found that any blackbody component with temperature in the range 0.5–1.5 keV, and carrying off more than 10% of the total 1–20 keV flux, is ruled out at the 99% confidence level.

2.4. *Spectra c, d*

For these two spectra, associated with the lowest 1–20 keV fluxes, the best fit is achieved by the combination of a hard power law and a cool blackbody (~0.5 keV) (see Table 2). The contribution of the blackbody component to the total 1–20 keV flux is 6% and 10% for spectra c and d, respectively. Assuming spherical geometry for the emitting region, we found an equivalent radius of 2.1 × $d_{2\,\mathrm{kpc}}$ km ($d_{2\,\mathrm{kpc}}$ distance in units of 2 kpc). This suggests that if the blackbody component originates from the neutron star surface, then only a limited region is involved.

2.5. *Spectrum e*

For observation e, none of the single-component models fits satisfactorily the data, the reduced χ^2 value being always very large (for the power law, reduced χ^2 of 49 for 36 d.o.f). When looking at the residuals (see Fig. 2 in the case of a power-law fit), it again immediately appears that this feature is reminiscent of the presence of a blackbody component. Inclusion of this component significantly improves all the fits, but the best fit of the underlying component remains a power law. The best fit (χ^2/d.o.f = 0.76/34) is thus a blackbody of temperature 1.5 keV and a power law of index 2.7. The 1–20 keV flux density

TABLE 2

BEST FIT PARAMETERS FOR THE *EXOSAT* SPECTRA OF 4U 0614+091 (Power Law + Blackbody)

PARAMETER	OBSERVATION IDENTIFICATION				
	a	b	c	d	e
Power-law photon index......	$2.15^{+0.03}_{-0.03}$	$2.24^{+0.03}_{-0.03}$	$1.96^{+0.09}_{-0.10}$	$1.86^{+0.10}_{-0.12}$	$2.72^{+0.1}_{-0.1}$
Blackbody kT (keV)...........	...	...	$0.54^{+0.12}_{-0.14}$	$0.50^{+0.09}_{-0.12}$	$1.51^{+0.04}_{-0.04}$
N_h (10^{22} cm^{-2})................	$0.38^{+0.07}_{-0.07}$	$0.38^{+0.07}_{-0.07}$	$0.21^{+0.32}_{-0.21}$	$0.22^{+0.32}_{-0.22}$	$0.53^{+0.16}_{-0.16}$
χ^2 (d.o.f)	9.6 (13)	13.7 (13)	8.9 (13)	8.8 (13)	25.9 (34)
Flux[a] (ergs cm^{-2} s^{-1}).........	1.5×10^{-9}	1.5×10^{-9}	1.2×10^{-9}	1.1×10^{-9}	3.9×10^{-9}
$F_{\mathrm{BB}}/F_{\mathrm{Tot}}$[b] (%)	≤10	≤10	5.9	9.8	25

[a] The flux is given in the 1–20 keV band.

[b] Ratio of the flux in the blackbody component to the total 1–20 keV flux. For observations a, b, the upper limits are computed for any blackbody temperature in the range 0.5–1.5 keV and are given at 99% confidence level.

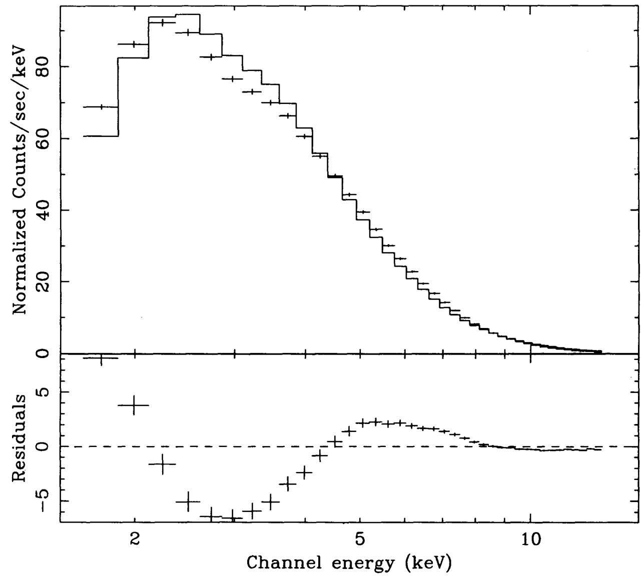

FIG. 2.—Residuals of a single power-law fit to the spectrum corresponding to the 1986 February 12–13 observation e. The shape of the residuals indicates the presence of a blackbody component.

carried off by the blackbody component is ~25% of the total flux. The equivalent radius of this component for a spherical emitter is 0.85 × $d_{2\,\mathrm{kpc}}$ km suggesting again that it is associated with a limited region of the neutron star surface.

For comparison, the best fit for a thermal bremsstrahlung model combined with a blackbody model yields a reduced χ^2 value of 2.9 (34 d.o.f) (N_h is not determined in the fit; a value of 0.4 × 10^{22} cm^{-2} has been assumed). This result indicates that even in the highest intensity state observed by *EXOSAT*, 4U 0614+091 was still characterized by a relatively hard spectrum. We suspect, as discussed below, that this is because this nearby source was still in a low-intensity state.

3. DISCUSSION

The *EXOSAT* spectra can be divided into three distinct sets. For the first set (spectra a, b), a power law of index 2.1–2.2 best describes the data. An upper limit of 10% has been derived on the contribution of any blackbody component with temperature in the range 0.5–1.5 keV. The 1–20 keV luminosity associated with these two spectra is ~7.2 × 10^{35} ergs s^{-1} at 2 kpc. The second set is made of two spectra corresponding to lower luminosities (~5.2 × 10^{35} ergs s^{-1}). Both are described by the sum of a hard power law and a cool 0.5 keV blackbody component contributing less than 10% of the total 1–20 keV flux. Finally, the third set consists of one spectrum e which is associated with the highest luminosity (~1.9 × 10^{36} ergs s^{-1}). The spectrum is then described by a steep power law (photon index ~2.7) and an intense 1.5 keV blackbody component. Figure 3 shows the photon spectrum corresponding to observations a "medium state," c "low state," and e "high state." The terminology here is confusing, since in all three cases, the X-ray luminosity is lower than 2 × 10^{36} ergs s^{-1}, and like the "low-state" of more distant bursters. Compared to previous soft X-ray data (Christian 1993), the X-ray flux associated with the high state is one of the highest ever measured from 4U 0614+091. The power-law spectral parameters inferred from the *EXOSAT* observations are in the range of those previously observed from the source (Christian 1993; Smale et al. 1992).

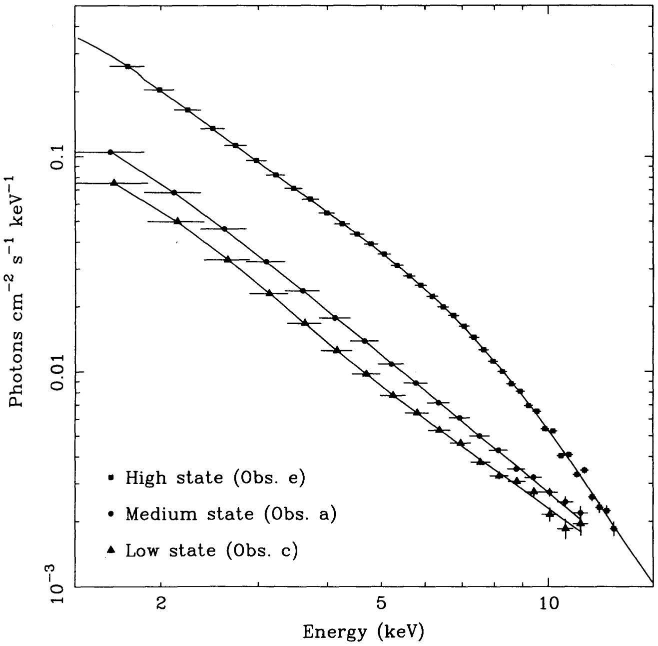

FIG. 3.—*EXOSAT* photon spectrum of 4U 0614+091 corresponding to three different intensity states. Between the low-state and the high-state spectrum the 1–20 keV flux increased by a factor of ~3.5.

4U 0614+091 enlarges the list of X-ray bursters displaying hard power-law spectra in their low-intensity state (see Barret & Vedrenne 1994 for the list). The present data on 4U 0614+091 show also that a relatively small increase in luminosity (a factor of 2.5) can lead to substantial spectral changes below 10 keV where the overall spectrum is modified by the presence of a relatively strong blackbody component. In the case of 4U 0614+091, the emission of this 1.5 keV blackbody component contributing about 25% to the total 1–20 keV flux is accompanied by a clear steepening of the spectrum, with the photon index changing from ~2.0 to 2.7. This result adds support to the idea that the emission of a blackbody component may cause, via Compton cooling, the quenching of the high-energy emission at high X-ray luminosity (i.e., at high accretion rate) as, for example, in the case of the bright *Z* sources. Blackbody emission could arise from either the neutron star surface or an optically thick boundary layer (see Hameury 1993 for a recent review). In this context, it is also worth noting that in the case of 4U 0614+091, in the lowest intensity states observed by *EXOSAT*, a blackbody component is detected together with a very hard spectrum (photon index ~2). Therefore, there may exist a critical luminosity for the blackbody component below which it is not strong enough to cool the hot electron population.

The data presented here clearly show that within the five observations, there is an *anticorrelation* between the power-law photon index (i.e., the hardness of the spectrum) and the X-ray flux in the 1–20 keV band (see Fig. 4). This *anticorrelation* which has now been observed from several X-ray bursters (see, for example, 4U 1705−44, Langmeier et al. 1987) appears more and more to be a common property of these objects and "Atoll sources" in general (van der Klis 1994). This also argues in favor of the Comptonization process being responsible for the observed spectral variations in the 2–20 keV band and above.

By simply extrapolating the power-law spectra observed by *EXOSAT* toward higher energies, significant and detectable

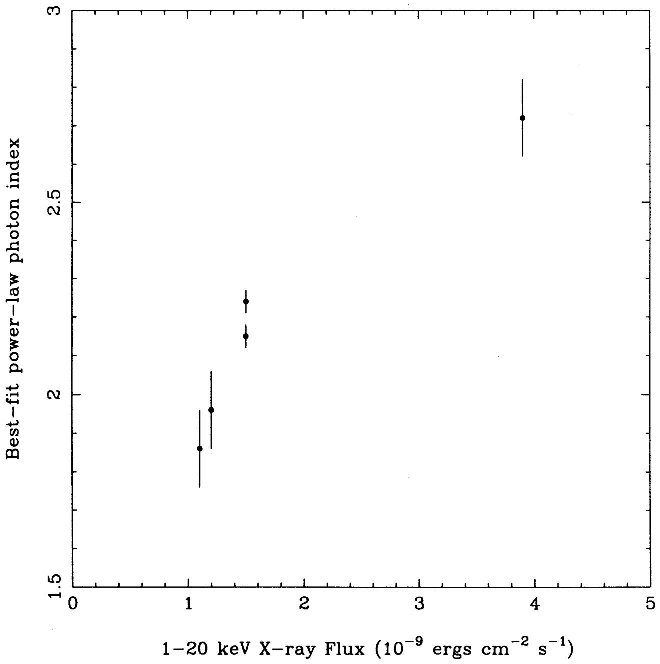

FIG. 4.—Evolution of the best-fit power-law photon index against the 1–20 keV flux. The data show a clear anticorrelation between hardness and intensity.

flux is expected above 30 keV, given the sensitivity achieved by current and previous hard X-ray detectors (at 100 keV typically 10^{-5} photons cm^{-2} s^{-1} keV^{-1}, for example, for SIGMA). We have looked at the *HEAO 1* A-4 All Sky Survey catalog (Levine et al. 1984) which contains the only available information on 4U 0614+091 in the hard X-ray range. This source, which was surveyed three times, is located in a relatively uncrowded region where confusion problems are unlikely. For the three *HEAO 1* A-4 observations spanning 1977 September through 1978 October, the source hard X-ray flux (13–25, 25–40, 40–80 keV) did not vary significantly, and in the sum of the three observations the source is detected in the 40–80 keV band. As can be seen in Figure 5 where we plot the average *HEAO 1* A-4 hard X-ray fluxes, this result is not surprising considering the flux expected from the extrapolations of the *EXOSAT* spectra. Note that because the *HEAO 1* A-4 fluxes (Fig. 5) are derived by Levine et al. (1984) assuming a Crab-like spectrum (i.e., E^{-2}), the spectral index for the A-4 data cannot be measured directly. However, it is worth noting that from simple hardness ratio analysis, 4U 0614+091 appears as one of the hardest X-ray bursters detected by *HEAO 1* A-4 (see van Paradijs & van der Klis 1994 for a comparison with other sources).

From the plotted value of the 13–25 keV flux, which is the most significant point in the *HEAO 1* A-4 data for the source, it is also clear that 4U 0614+091 was observed by *HEAO 1* A-4 at a very low intensity state, significantly lower than that corresponding to any of the *EXOSAT* observations reported here. We were unable to determine the X-ray state of the source at the time of the A-4 observations, since there are no simultaneous *HEAO 1* A-2 MED (1–15 keV) spectral data available for 4U 0614+091. Although we have to be cautious, due to the absence of simultaneous X-ray data, the *HEAO 1* A-4 results support the idea that neutron star LMXBs emit hard X-rays in their lowest intensity states, as suggested by Barret & Vedrenne (1994). Furthermore, they appear to be consistent with the global anticorrelation observed by *EXOSAT* at lower energies. Finally, as suggested by the apparent hardness of the *HEAO 1* A-4 fluxes (i.e., from hardness ratio values), it is unlikely that the hard X-ray power-law tail seen by *HEAO 1* A-4, and expected from the hardness-intensity anticorrelation seen by *EXOSAT*, has a spectral break or a high-energy cutoff below ~80 keV.

4. CONCLUSIONS

4U 0614+091 joins the list of X-ray bursters displaying hard power-law spectra (photon index ~2) when their X-ray luminosity is low. Furthermore, the source displays a clear anticorrelation between spectral hardness and X-ray flux. The results presented here are consistent with the idea that a strong blackbody emission, which led in the case of 4U 0614+091 to a clear steepening of its soft X-ray spectrum, may be able to quench the high-energy emission in neutron star systems. They also suggest that X-ray bursters are emitting hard X-ray tails when they reach low-intensity states. This hypothesis is supported by the results provided by *HEAO 1* A-4 which detected the source up to 80 keV (at its sensitivity limit), when the source was probably in a very low state.

It is possible that all bursters at low-accretion rates emit a significant fraction of their total luminosity in the poorly observed 20–200 keV range with power-law spectra with photon index ~2–3 and energy cutoffs above 100 keV. The total luminosity of X-ray bursters would be therefore significantly larger than usually assumed for their "low state." This may have important implications on the X-ray heating of their close binary companions, as well as the total (hard) X-ray luminosity of these systems in the Galaxy.

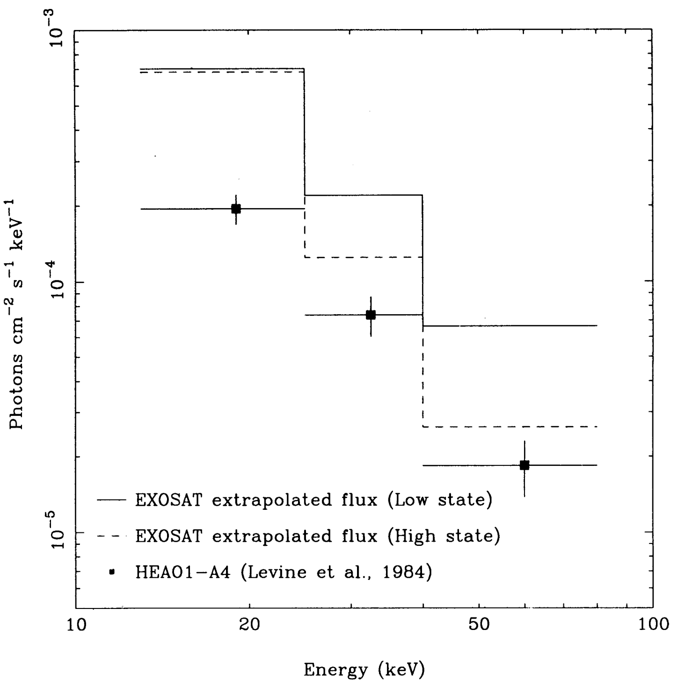

FIG. 5.—Comparison of the *HEAO 1* A-4 hard X-ray fluxes with the fluxes expected from the extrapolations of the *EXOSAT* spectra associated with the lowest and highest intensity state.

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Note added in proof.—Just after this paper was accepted for publication, we found a paper by K. P. Singh & K. M. V. Apparao (ApJ, 431, 826 [1994]) reporting on the same archival *EXOSAT* observations of 4U 0614+091. By studying hardness ratios they showed that 4U 0614+091 resembles "Atoll sources" with the "island" state associated with the hardest X-ray spectra, and the "banana" state corresponding to the softer (though still hard) spectrum. It is noteworthy that this feature has been observed from several "Atoll sources" (e.g., see 4U 1705−44, 4U 1608−522, 4U 1820−30). This suggests that the "island" state may be the state for which these sources emit hard X-ray tails. As for the spectral analysis although we followed a slightly different approach (energy range for the fitting, models considered) our results are obviously consistent with those presented in their paper. However, our paper differs in pointing out clearly the hardness-intensity relation and the constraints this source provides on hard X-ray tails from bursters.