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GX 339-4: EXOSAT observations in the off and soft states

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Summary. We present observations made with the EXOSAT satellite of the highly variable low-mass X-ray binary GX 339-4 obtained during two radically different states. During an off state in April 1985 we found the source to be very weak (1.5 μJy) and to exhibit a hard power-law spectrum (photon index = 1.8). We compare this to observations made during its characteristic soft state in May 1984, which show a bright source (83 μJy) with a two-component spectrum featuring a very soft unsaturated Comptonized component ($E^{-m}\,e^{-E/kT}$) and a power-law tail. During the soft state we set an upper limit of 0.8% on any X-ray variability from 1 s to 6 h. The two states differ in intrinsic 0.1–20 keV luminosity by a factor of 140, while the optical luminosity changes by a factor of 2.5. We find a good correlation between the optical luminosity and the luminosity of the power-law spectrum, including the hard tail in the soft state. Using soft X-ray measurements we obtain an X-ray absorption column of $N_H = 5\ 10^{21}\ \mathrm{cm}^{-2}$ in both states, implying a lower limit of 2 kpc for the distance to the source. The spectral changes we see in GX 339-4 are similar to those exhibited by "ultra-soft" X-ray transients such as 4U 1630-47, and are clearly governed by changes in the accretion rate. The off state power-law is similar in slope to that seen in the bright hard state, consistent with the belief that both are produced in a hot cloud region by inverse Compton collisions on soft photons when the accretion rate is low. The difference in luminosity by a factor of 100 between the two hard states shows significant changes take place in the accretion disk. We suggest the power-law spectra, the hard tail seen during the soft state, when the accretion rate is presumably high, and the optical emission may have a common origin.

Key words: X-ray sources – low-mass binaries – spectra – transients

1. Introduction

In the discovery observations of GX 339-4 with the satellite OSO-7, Markert et al. (1973) reported on three different 2–10 keV states for this source: high, low and off. The difference between the first two states was soon recognized as due to changes in the spectrum: very soft in the high state and hard in the low state (Markert et al., 1973; Jones, 1977; Doxsey et al., 1979; Ricketts, 1983), in a manner analogous to Cygnus X-1 (Tananbaum et al., 1972; Sanford et al., 1975). Attendant to these spectral changes are remarkable changes in time variability: rapid (as short as 50 ms) fluctuations during the hard (or low) state (Samimi et al., 1979; Motch et al., 1983; Maejima et al., 1984) and total absence of short-time (0.1–100 s) variability in the soft (or high) state (Forman et al., 1976; Li et al., 1978; Maejima et al., 1984; Makishima et al., 1985).

Between 1981 and 1985 observations of the optical counterpart identified by Doxsey et al. (1979) have demonstrated the existence of recognizable optical states corresponding to the X-ray states (Motch et al., 1983, 1985). In particular, during the X-ray off states of March–April 1981 and May 1982 (Maejima et al., 1984) the optical object was found faint. In March 1981 it reached a record low (Ilovaisky and Chevalier, 1981) of $B = 20.3 \pm 0.1$ (new estimate based on the original Schmidt plate and a recent deep CCD sequence in the field). In May 1982 we found it moderately faint ($B = 18.4$) and active, with 7 s quasi-periodic oscillations (Motch et al., 1985). During an observing at the European Southern Observatory (ESO) on late March 1985, we found the optical star again in this faint state, which lasted at least through 29 April 1985 (Boisson, 1985), when an EXOSAT observation was made. Optical fast photometry (10 ms resolution) obtained on 24–25 April 1985 with the ESO 3.6 m telescope reveals the presence of quasiperiodic oscillations at 18 s (Mouchet and Angebault, 1985). The detailed results of the optical observations will be reported elsewhere.

No detailed X-ray observations of an off state have ever been previously reported. In what follows we present EXOSAT observations made during such an off state and compare them with other observations made with the same instrumentation during the soft state.

2. The April 1985 off state

Two different pointings of GX 339-4 were made in April 1985 within a 4 day interval with the source being very weak on both occasions. The first observation took place on 25 April 1985 during a period of increased solar activity which prevented use of the proportional counters. Only two brief observations were made using the low-energy telescope and channel multiplier array CMA (LE, see de Korte et al., 1981), at the beginning and end of a 6^h pointing. The second observation was made between 12^h and 18^h UT on 29 April 1985 after the activity had subsided. We present here data taken with the medium-energy Argon proportional counters (ME, see Turner et al., 1981), together with com-

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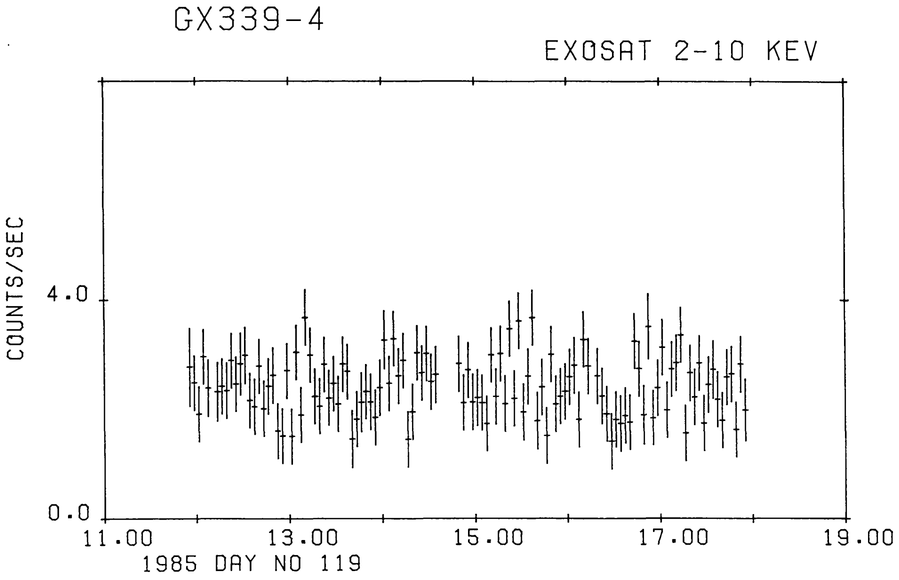

Fig. 1a. Background-subtracted light curve of GX 339-4 based on EXOSAT observations obtained with the Medium-Energy experiment on 29 April 1985 during an off state. Data points are 3-min averages of Argon detector counts in the 2–10 keV band. ±1 σ error bars are shown. Note the interruption about half-way due to an array swap. The source is steady during the 6-hour observation at 2.4 ± 0.2 c s half array^{-1}. See the text for an explanation of the background subtraction techniques. Time is given in hours (U.T.)

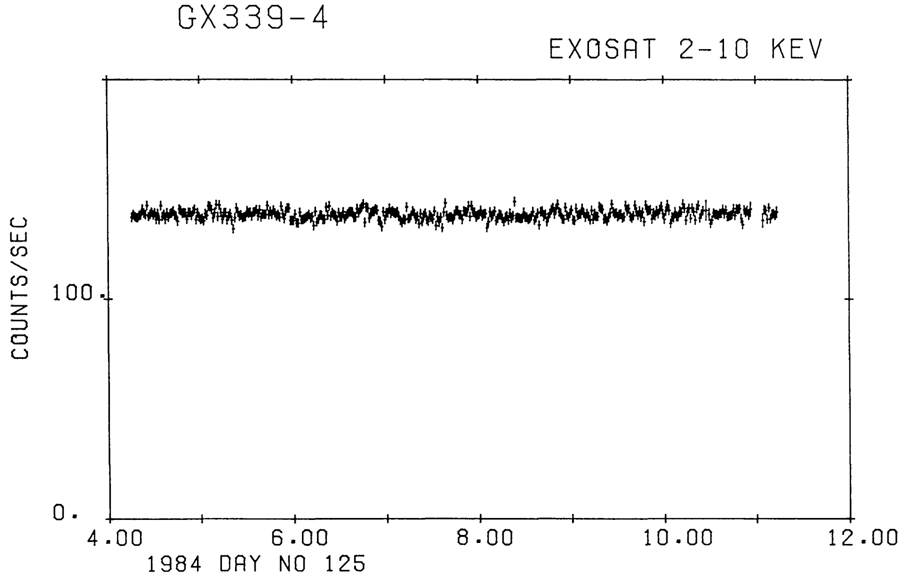

Fig. 1b. Background-subtracted light curve of GX 339-4 obtained with EXOSAT on 7 May 1984 during a soft state. Data points are 1-min averages. Error bars are as given above. The average source count rate is 139 ± 1 c s^{-1} half array^{-1}. Labeling is the same as in the previous figure

plementary data from the low-energy telescope, as the source was detected on both occasions with this instrument. For a complete description of the EXOSAT payload, see Taylor et al. (1981).

The ME collimator array was operated in an offset configuration, with one-half aligned on the source (750 cm^2 effective area) and the other half offset for background measurements. Midway during the observation an array swap was made. No other sources were present in the 45′ FWHM field of view of the ME, as derived from the analysis of the CMA images. ME Argon data were acquired using the MHER 4 mode, in which 128-channel spectra with detector identification are read out every 10 s.

In Fig. 1a we present the light curve derived by summing the 2–10 keV data in 3 minute averages. The background correction was done by subtracting counting rates of the offset half from those of the on-source half after proper correction for the known offset-angle dependence of the instrumental background and for the intrinsically different particle backgrounds of the two halves of the ME. The agreement between the data from the two halves confirms the correctness of the background subtraction procedure and shows the source was steady, within counting statistics, at an average count rate of 2.4 ± 0.2 c s^{-1} half^{-1} during the full 6 h. A power spectrum of these data shows no statistically significant periodic or quasi-periodic components up to the Nyquist frequency of 50 mHz. For aperiodic variations we derive an (1 σ) upper limit of 26 % on any variations on time scales from 20 s to 6 h. Due to the extreme weakness of the source, we conclude that no meaningful upper limit can be set to any variability, in particular of the type seen in May 1981 and normally associated with hard states (Samimi et al., 1979; Motch et al., 1983).

For each half of the ME the offset background spectra were corrected for the offset-angle dependence and were subtracted from the on-source spectra, which were then added together. This count-rate spectrum was found to be hard. A single-component photon continuum model consisting of a power-law spectrum,

$$S(E) = a_1 E^{-n} e^{-\sigma(E) N_H} \text{ photons cm}^{-2}\,\text{s}^{-1}\,\text{keV}^{-1},$$

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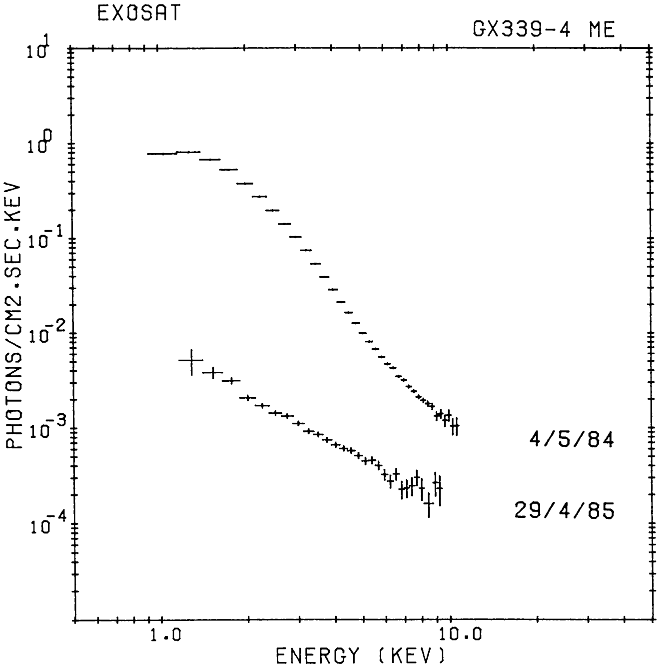

Fig. 2. Incident spectra of GX 339-4 obtained with the Argon counters of the EXOSAT Medium-Energy experiment on 4 May 1984, during a soft state (upper curve) and on 29 April 1985, during an off state (lower curve). The spectra are shown at their true levels. ± 1 σ error bars are shown. Note the power-law shape during the off state and the power-law tail that accompanies the soft state spectrum. See the text for a discussion of the background subtraction techniques and for details of the photon input model spectra that were fit to the data

folded through the detector response function was fitted to the data using minimum χ^2 techniques. The model included absorption in the line of sight due to cold material with cross sections $\sigma(E)$ taken from Morrison and McCammon (1983). A 1% systematic uncertainty was included in the spectral fitting to allow for systematic uncertainties in the ME calibration. A formal best fit was obtained for $n = 1.7$ and no absorption (reduced $\chi^2 = 0.69$).

As the ME is not very sensitive to low absorption columns, a joint fit was made using both the LE and ME data. For the entire 6 h observation an image was accumulated using the CMA and the 3000 Å lexan filter. The average count rate, $0.35 \pm 0.05\,\mathrm{c\,min^{-1}}$, was estimated by integrating counts in a box centered on the source with background being estimated from the surrounding area. Analysis of the shorter LE observation obtained on 25 April shows that the count rate, $0.34 \pm 0.08\,\mathrm{c\,min^{-1}}$, agrees with the longer observation, indicating that the source did not vary significantly in soft (0.1–0.3 keV) X-rays over the 4-day interval. In combining the LE and ME data a 5% systematic uncertainty was assumed in the LE data to allow for systematic errors in the relative detector calibrations. The results of the joint fit yield a power-law of photon index $n = 1.85 \pm 0.15$ and an absorption column of $N_{\mathrm{H}} = 5.0$ $(\pm 0.7)\ 10^{21}\,\mathrm{cm^{-2}}$ (reduced $\chi^2 = 1.07$). The resulting incident spectrum is shown in Fig. 2 (lower curve). The 2–10 keV flux density observed at Earth is $2.9\ 10^{-11}\,\mathrm{erg\,cm^{-2}\,sec^{-1}}$, corresponding to 1.5 μJy.

Samimi et al. (1979) have reported detection of 1–20 keV emission from GX 339-4 with the HEAO satellite A-1 experiment at the 2 μJy level in March 1978. Nolan et al. (1982) have reported on the HEAO satellite A-4 observations made between 20 and 200 keV simultaneously with those of Samimi et al. and although they a derive a power-law spectrum of photon index 2.27 ± 0.27, obtained when the A-1 experiment saw the source in an off state, this spectrum violently disagrees with the A-1 flux: the extrapolation of the power-law spectrum down to 1–10 keV gives too strong a flux by a factor of 20. Contrary to the conclusions of Nolan et al. we find that absorption is not the answer. The only way to reconcile the A-1 and A-4 data would be to introduce a break in the power-law at 10 keV, but then the 1–10 keV spectrum would have to be flat, an unusual situation and clearly in disagreement with our findings. We thus suspect that some systematic effect went unnoticed and cannot unfortunately compare their interesting high-energy results with ours.

Using the average relation found between visual absorption and X-ray absorption column (Gorenstein, 1975; Ryter et al., 1975), our observed value of N_{H} yields $A_V = 2.2 \pm 0.3$ mag, implying $E(B-V) = 0.7 \pm 0.1$ mag, compatible with the maxium visual absorption observed in this direction, $A_V = 1.5 \pm 0.3$ mag (Neckel and Klare, 1980). At the galactic latitude of GX 339-4, the line of sight clears the bulk of the absorption layer (of scale-height 150 pc) at about 2 kpc. We thus conclude that the absorption measured in April 1985 is purely interstellar and that the source distance is $\geqq 2$ kpc. Hayakawa (1981) reported a soft X-ray measurement with the Hakucho satellite of GX 339-4 during the soft state with an absorption column identical to ours. During the May 1981 hard state, Ricketts (1983) derived a low but compatible amount of absorption ($< 2\ 10^{21}\,\mathrm{cm^{-2}}$) although badly determined due to the lack of soft X-ray measurements. Our value for the color excess derived from N_{H} is in good agreement with that needed ($E(B-V) = 0.66$) to deredden the X-ray and optical energy distributions of the May 1981 hard state to a common power law of photon index 1.58 (Motch et al., 1985).

For a source distance of 2 kpc the observed flux density in the faint hard state gives an intrinsic source luminosity, corrected for interstellar absorption, of $L(0.1\text{–}20\,\mathrm{keV}) = 4.6\ 10^{34}\,\mathrm{erg\,s^{-1}}$. Note that although the spectra of the off state and the bright hard state of May 1981 have comparable power-law indices indicating a common X-ray emission mechanism, the difference in luminosity between the two states is more than a factor of 100.

3. The May 1984 soft state

A 6-hour EXOSAT observation of GX 339-4 was obtained in an offset configuration on 7 May 1984 between 7^{h} and 16^{h} UT, during a typical soft state. There was no array swap and the background corrections were made using good slew data. ME Argon data were taken in the MHER 5 mode, where 64-channel spectra were accumulated every 0.625 s. A light curve (Fig. 1 b) constructed from the 2–10 keV channels shows a remarkably steady source with a count rate of $139 \pm 1\,\mathrm{c\,s^{-1}\,half^{-1}}$. Power spectra were found to be consistent with Poisson statistics in the frequency range 0–800 mHz. We derive a 1 σ upper limit of 0.8% on any variability on time scales from 1.2 s to 6 h. This demonstrates the total absence in the soft state of the rapid activity seen during the bright hard state, in agreement with previous observations (Forman et al., 1977; Li et al., 1978; Maejima et al., 1984; Makishima et al., 1985). A detailed analysis of high time resolution intensity data will be reported separately.

The count rate spectrum derived for the 6-hour observation, obtained by subtracting background spectra obtained during the slews, was found to be very soft and complex. A 1% systematic uncertainty in the spectral fits was also included here. This time, however, the fits using single components failed largely to account for the observations: a single power-law fit as described above yielded $n=4.5$ ($\chi^2=557$ for 33 degrees of freedom) and an exponential (thin bremsstrahlung) spectrum gave $kT=1.4$ keV ($\chi^2=2614$ for 32 d.o.f.), with different degrees of absorption. The disagreement with the data was largest in the bins above 6 keV.

During this observation soft X-ray data were acquired with the CMA and 3000 lexan, aluminium/parylene and boron filters, which have different spectral responses. The count rates derived, $1.68\pm0.02\,\mathrm{c\,s^{-1}}$, $1.19\pm0.02\,\mathrm{c\,s^{-1}}$, and $1.04\pm0.01\,\mathrm{c\,s^{-1}}$, were used in joint spectral fits with the ME data. A 5% systematic uncertainty was again introduced when combining them with the ME data.

Different two-component photon continuum models were then tested. A combination of a soft unsaturated Comptonized spectrum (White et al., 1985, 1986) and a power-law at higher energies,

$$S(E)=(a_1E^{-m}e^{-E/kT}+a_2E^{-n})\,e^{-\sigma(E)N_\mathrm{H}}\ \text{photons cm}^{-2}\,\mathrm{s}^{-1}\,\mathrm{keV}^{-1},$$

was found to best fit the data, although the fit was not excellent (reduced $\chi^2=1.7$). The introduction of a broad iron emission line at 6.4 keV improved the fit (reduced $\chi^2=1.1$). Leaving all parameters free we obtained $m=0.7\pm0.2$, $kT=0.80\pm0.07$ keV, $n=2.2\pm0.2$. The absorption column was again found to be $N_\mathrm{H}=5.0\,(\pm0.2)\,10^{21}\,\mathrm{cm}^{-2}$. The net effect of including the line was to flatten the power-law somewhat. The iron line equivalent width was 170 ± 100 eV (very uncertain). The resulting incident spectrum is shown in Fig. 2 (top).

Similar results have been obtained by Makishima et al. (1985) from the Tenma Satellite Gas Scintillation Proportional Counter (GSPC) observations made during the soft state of May 1983. Although Makishima et al. fitted a different photon continuum model (their disk black-body model) the over-all description of the data is the same. They found the slope of the power-law component to vary in a matter of days (between 0.9 ± 0.5 and 2.1 ± 0.2). The 10 keV flux of our hard component ($1.5\,10^{-4}$ photons cm^{-2} s^{-1} keV^{-1}) lies within the values observed by Makishima et al. ($5\,10^{-4}$ to $2\,10^{-3}$ photons cm^{-2} s^{-1} keV^{-1}). Our iron emission line equivalent width is three times theirs, but could be consistent taking into account our errors. We note that in Cygnus X-1 Barr et al. (1986) have discovered with the EXOSAT GSPC a strong broad iron emission line at 6.2 keV having an equivalent width of 120 eV. Analysis of the EXOSAT GSPC data on GX 339-4 will be presented elsewhere.

The intrinsic luminosity during this soft state, corrected for interstellar absorption, is $L\,(0.1\text{–}20\,\mathrm{keV})=6.6\,10^{36}\,\mathrm{ergs\,s^{-1}}$, again assuming a 2 kpc distance to the source. The ratio between the intrinsic luminosities of the soft and power-law components, $L_\mathrm{soft}/L_\mathrm{hard}$, is roughly 16. The flux density at Earth in our data in the 2–10 keV band is $1.6\,10^{-9}\,\mathrm{erg\,cm^{-2}\,s^{-1}}$, equivalent to 83 μJy, fainter than seen either by Tenma in May 1983 (350 μJy) or Ariel 6 in June 1979 (260 μJy).

4. The spectral changes

The spectral changes observed up to now Cygnus X-1 and GX 339-4 ("bimodal" behavior) corresponded to changes in slope but little change in luminosity (Sanford et al., 1976 and Ricketts, 1983). The "pivot" energy, that is the energy at which the flux remained constant during such a state transition, is 6 keV for GX 339-4 (Ricketts, 1983) and 3 keV for Cygnus X-1 (Chiappetti et al., 1981). The off-state spectrum of GX 339-4 we obtained in April 1985 is not cosistent with this simplified view. The slope observed in April 1985, close to 1.8, ressembles that of the May 1981 bright hard state, about 1.6 (Motch et al., 1984), suggesting that the same X-ray emission mechanism is at work in both cases; however, the difference in intrinsic luminosity between these states is more than two orders of magnitude, indicating that severe changes have taken place in the accretion disk.

The spectral changes we find between the soft and the off states of GX 339-4 strongly resemble those seen in "ultra-soft" X-ray transients (White Kaluzienski and Swank, 1984), in particular 4U 1630-47 (Parmar et al. 1985). The spectral evolution of this source shows that, when bright, its spectrum was dominated by a soft component approximated by an unsaturated Comptonized spectrum ($m=-1.8\pm0.4$, $kT=1.2\pm0.1$ keV) plus a power-law tail ($n=2.5\pm0.1$). As the source declined in intensity, the very soft component decreased (and finally disappeared) relative to the power-law, which itself flattened as the source faded, reaching $n=1.2\pm0.2$ three months after outburst. There is a difference, however, between 4U 1630-47 and GX 339-4, and it concerns the rapid X-ray flux variability, which is absent in GX 339-4 during the soft state, but was strikingly present in 4U 1630-47 in its soft component at maximum.

Similar soft/hard spectral behavior has been observed with the Hakucho Satellite in Circinus X-1 and in the bright transient 4U 1608-52 (Tanaka, 1986). The latter is a well-known burst source (Murakami et al., 1980) while EXOSAT observations of Circinus X-1 have now shown it to burst as well (Tennant et al., 1986).

In the two-temperature accretion disk model originally conceived for Cygnus X-1 (Shapiro et al., 1976; Ichimaru, 1977; Eardley et al., 1978; Guilbert and Fabian, 1982), and later applied to GX339-4 (Fabian et al., 1982), it has been argued that the soft component comes from the inner regions of the accretion disk, where copious soft photons (coming from the outer parts of the disk) are Compton up-scattered in hot clouds, but without attaining the highest energy possible (i.e. the optical depth of the clouds is not large).

In this model the spectral changes (bimodal behavior) are related to changes in $t_\mathrm{esc}/t_\mathrm{cool}$, the ratio of the escape time of the soft photons from the clouds to the cooling time of the clouds, due to the presence of these soft photons. This ratio is governed by the total amount of soft photons available, presumably related to the accretion rate which controls the size of the accretion disk. When the soft photon luminosity is low the clouds cool slowly and the photons can reside sufficiently long to be up-scattered into the 100 keV range, yielding a rather flat power-law spectrum typical of the hard state (Eardley and Lightman, 1976; Guilbert and Fabian, 1982). The rapid X-ray variability seen during the bright hard state has been associated with the short cooling times of individual clouds (Fabian et al., 1982). When the soft photon luminosity increases, the clouds cool faster and the photons cannot complete the full up-scattering process, yielding a much steeper spectrum, typical of the soft state. The absence of rapid X-ray variability in this state implies the rapid destruction of the clouds or, alternatively, masking of the remaining hot cloud region by a thickening of the disk.

It has been suggested that the hard tails present in the soft spectrum sources could be due to comptonized bremsstrahlung from the cooling clouds (Guilbert and Fabian, 1982) or to Comptonization of the soft X-ray component itself (Makishima et al., 1985). One would then expect the tail to be seen only when this soft component is present. Our April 1985 observation shows a power-law spectrum with a photon index 1.85 ± 0.15, virtually indistinguishable from the slope of the power-law tail (2.2 ± 0.2) in

Table 1. X-ray and optical luminosities of GX 339-4 in the hard, soft and off states[a]

	Hard state[b] March 1981	Soft state May 1984	Off state April 1985
S_X(2–10 keV aver.)	250 μJy	83 μJy	1.5 μJy
L_X(0.1–20 keV)[c]	4.8 10^{36} erg s^{-1}	6.6 10^{36} erg s^{-1}	4.6 10^{34} erg s^{-1}
L_X(hard) (keV)[d]	4.8 10^{36} erg s^{-1}	3.8 10^{35} erg s^{-1}	4.6 10^{34} erg s^{-1}
B-magnitude	16.2[e]	17.7[f]	18.8[f]
$B–V$ color index	0.8	0.9	1.1
$L_{\rm opt}$(3700–6500 Å)[g]	3.5 10^{34} erg s^{-1}	9.5 10^{33} erg s^{-1}	3.9 10^{33} erg s^{-1}
L_X(hard)/$L_{\rm opt}$	140	40	10

[a] Assuming a distance of 2 kpc (see text)
[b] Ariel 6 observations (Motch et al., 1983 and Ricketts, 1983)
[c] Corrected for interstellar photoelectric absorption ($N_h = 5\ 10^{21}\ \rm cm^{-2}$)
[d] Obtained by integrating the power-law given by the fits between 0.1 and 20 keV
[e] Photoelectric photometry (Motch et al., 1981: IAU Circular No. 3609)
[f] CCD photometry (see text)
[g] Corrected for interstellar extinction ($A_V = 2.2$ mag, $E_{B-V} = 0.7$)

the soft state. Moreover, Makishima et al. (1985) report that the hard tail spectral slope of GX 339-4 varied from 0.9 ± 0.5 to 2.1 ± 0.2 as the strength of this component increased by more than a factor of 10. This range includes both the off state (1.8) and May 1981 hard state (1.6) values, showing that we can probably identify the hard state spectrum, the off state spectrum and the high-energy tail of the soft spectrum with the same emission mechanism. The evolution of the spectrum of 4U 1630-47 strengthens this view.

5. X-ray to optical luminosity ratio

Photometry obtained by us near the times of the EXOSAT observations allows a comparison between the changes in optical (3700–6500 Å) and X-ray luminosity associated with the changes in total X-ray emission. CCD photometry was obtained with the ESO 2.2 m telescope on 6 May 1984, two days after the EXOSAT soft X-ray observation reported here, when the object was found at $B = 17.7$, and with the ESO 1.54 m Danish telescope on 25–27 March, 21 and 29 April 1985, the latter hours before the off state observations, giving a values ranging from $B = 18.7$ to 18.9.

We give in Table 1 a summary of the data and values for the luminosities at both wavebands for the three states of GX 339-4. When the source was in its soft state of May 1984 $L_X/L_{\rm opt}$ was close to 700, while the value fell to about 10 in the off state of April 1985. In comparison this ratio was roughly 140 during the May 1981 bright hard state. As mentioned in Sect. 1 the June 1981 hard to soft X-ray transition studied by Hakucho (Maejima et al., 1984) was accompanied by a decrease in optical luminosity (Motch et al., 1985). This immediately suggests that the optical flux is directly related to the strength of the power-law component. Using the data in Table 1 we derive a good correlation between the *optical* luminosity and the X-ray luminosity of the *hard* component. This agrees with our finding that a single power-law can fit the X-ray, optical and IR energy distributions of GX 339-4 during the May 1981 hard state (Motch et al., 1985). The above facts are clearly incompatible with a simple interpretation of the optical emission in terms of X-ray reprocessing in the accretion disk and support the idea that the a large fraction of the optical luminosity may be generated by the same mechanism responsible for the X-rays, or by a related process, such as cyclotron radiation from hot magnetized clouds (Fabian et al., 1982).

6. Conclusions

An EXOSAT observation of GX 339-4 made during a soft state reveals the X-ray spectrum to be composite, with a very soft component, approximated by an unsaturated Componized spectrum, and a power-law which dominates at higher energies. Another EXOSAT observation, made for the first time during an off state, reveals a very weak source (1.5 μJy) with a simple power-law spectrum of index of 1.8. The difference in X-ray luminosity between these states is about 140. This behavior and the associated spectral changes are similar to those of "ultra-soft" X-ray transients, such as 4U 1630-47 and are obviously related to changes in the accretion rate, triggered either by instabilities in the low-mass, low-luminosity companion or by instabilities in the disk. The discovery of similar spectral changes in 4U 1608-52 and Circinus X-1, which exhibit X-ray bursts, shows that bi-modal spectral behavior is not necessarily associated with accretion onto black holes but can also be found in systems with accreting neutron stars.

The off state spectrum has a slope similar to that of the bright hard state spectrum of May 1981, implying that both correspond to low accretion rates. However, the difference in luminosity is a factor of 100, implying large changes in the accretion disk between these states. Assuming the hard spectrum is produced by inverse Compton collisions between soft photons and electrons in hot (10^9 K) clouds in the disk when the accretion rate is low, the existence of a power-law tail in the soft state spectrum, when the accretion rate is high, shows that a sizeable (but variable) fraction of the clouds remains hot.

The large variations seen in $L_X/L_{\rm opt}$ as GX 339-4 goes from the soft to the off state preclude a simple explanation of the optical flux in terms of reprocessing of X-rays. We find the optical flux to be correlated with the X-ray luminosity of the power-law spectrum, including the tail of the soft state, thus supporting the view that a large fraction of the optical flux, at least during the hard and off states, is produced by the same mechanism as the X-ray flux, or by a related process.

Future X-ray astronomy missions with larger collecting areas, such as XSM, Astro-C and XTE, should allow one to detect the off state of the rapid variability characteristic of the bright hard state and associated with the short lifetimes of the hot clouds. They should also make possible a search for such variability in the hard tail seen during the soft state.

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