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ROSAT observations of soft X-ray transients in quiescence

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Abstract. Aql X-1 has been detected in five observations with ROSAT, at X-ray luminosities varying from $L_x(0.4-2.4\,\mathrm{keV}) \sim 4\times10^{32}\,\mathrm{erg\,s^{-1}}$ to $\sim 2\times10^{36}\,\mathrm{erg\,s^{-1}}$. The characteristic temperature of the X-rays varies from $kT_{bb} \simeq 0.31\,\mathrm{keV}$ at the lowest to $kT_{bb} \simeq 0.55\,\mathrm{keV}$ at the highest flux level observed. This moderate temperature variation excludes models that explain the large range in X-ray luminosity as the consequence mainly of a variation in temperature, and implies that accretion onto the neutron star drops by five orders of magnitude between outburst maximum (at $L_x \sim 10^{37}\,\mathrm{erg\,s^{-1}}$) and quiescence. Three other soft X-ray transients, all black hole candidates, were also observed with ROSAT. GS 2023 + 338 was detected at $L_x(0.4-2.4\,\mathrm{keV}) \simeq 1.5\times10^{33}\,\mathrm{erg\,s^{-1}}$ (for a distance $d = 3.5\,\mathrm{kpc}$). For H 1705 − 25 an upper limit of $L_x \lesssim 4.9\times10^{32}\,\mathrm{erg\,s^{-1}}$ ($d = 3\,\mathrm{kpc}$) was obtained, and for GS 2000 + 25 an upper limit of $L_x \lesssim 1.0\times10^{31}\,\mathrm{erg\,s^{-1}}$ ($d = 2\,\mathrm{kpc}$).

Key words: X-rays: stars – accretion – stars: GS 2023+338, Aql X-1, H 1705-25; GS 2000+25

1. Introduction

In low-mass X-ray binaries a neutron star or black hole accretes matter from a low-mass companion. Some such binaries are detected as transient X-ray sources, in outbursts during which the X-ray luminosity first rises in a few days to a level similar to those observed in permanently bright sources, and then declines on a time scale of several months. The intervals between the outbursts are irregular, or semi-regular, and vary from about a year in some sources to half a century in others. For some transients only one outburst is known. Between outbursts the X-ray flux levels drops below the detection limits of early X-ray satellites. Reviews of soft X-ray transients are given by White et al. (1984) and van Paradijs & Verbunt (1984). Those with black hole candidates are reviewed by Tanaka & Lewin (1994).

The absence of sensitive X-ray studies during the quiescent intervals between outbursts has hampered theoretical understanding of the outburst mechanism. The drop by a factor $\gtrsim 10^3$ in X-ray luminosity between outburst maximum and quiescence may directly reflect a drop in the accretion rate $\dot{M}$ onto the compact object, as the luminosity L liberated by accretion onto a compact object of mass M and radius R may be estimated with

$$L = \frac{GM\dot{M}}{R} \tag{1}$$

If the surface area that emits the accretion luminosity is comparable to that of the compact object, we may further write

$$L \sim 4\pi R^2\sigma T_{\rm eff}^4 \tag{2}$$

A drop in $\dot{M}$ thus may not only lead to a lower luminosity, but also to a lower temperature, which may cause most of the luminosity to be emitted at photon energies below the range of X-ray detectors. In addition this radiation is subject to much stronger interstellar absorption. Therefore, it is possible that the precipitous decline in X-ray flux actually reflects a moderate drop in $\dot{M}$ (de Kool 1988).

In Table 1 we summarize the previous detections and sensitive upper limits of soft X-ray transients in quiescence. Quiescence here is taken to mean that the X-ray flux has dropped by more than three orders of magnitude with respect to the maximum observed level during outburst. The luminosities quoted in the literature refer to a variety of bandpasses, as they are based on observations with a variety of detectors. To compare the X-ray luminosities of different transients, we convert all of them into luminosities between 0.4–2.4 keV, using the spectral parameters assumed by the authors listed in Table 1. It should be noted that the conversion of the luminosity from one energy range to another can be quite wrong, if the spectral parameters

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Table 1. Previously published detections and deep upper limits of soft X-ray transients in quiescence, as culled from the literature. The columns give the source name, the (upper limit to the) flux that would reach the Earth if no interstellar absorption were present (i.e. $F_x \equiv L_x/(4\pi d^2)$), the energy range in which this flux was determined, the spectral parameters and column density used to translate countrate into flux, and the reference. We use these same spectral parameters and fluxes to predict the countrates in channels 41-240 of the ROSAT PSPC, given in the last column. Abbreviations: BR = thermal bremsstrahlung, approximated by us with energy flux $f_\nu \propto \nu^{-0.3} \exp(-h\nu/kT)$ for the calculation of PSPC predicted countrates. PL = power law, $f_\nu \propto \nu^{-\alpha}$. EX = exponential, $f_\nu \propto \exp(-h\nu/kT)$. BB = blackbody. References: 1. Van Paradijs et al. 1987, 2. Czerny et al. 1987, 3. Hertz & Grindlay 1983, 4. Mineshige et al. 1992, 5. Long et al. 1981.

source	$F_x \equiv \int f_\nu d\nu$ (erg cm^{-2} s^{-1})	range (keV)	N_H 10^{21} cm^{-2}	spectrum	ref	predicted PSPC cts/s
Cen X-4	$2.4 - 6.6 \times 10^{-12}$	0.5-4.5	0.66	BR $kT = 1 - 5$ keV	1	0.15-0.28
Aql X-1	2.1×10^{-11}	1.2-10.	0.0	PL $\alpha = 1.5$	2	2.6
	$< 2.0 - < 4.0 \times 10^{-12}$	0.5-4.5	2.4	BR $kT = 1 - 5$ keV	1	<0.08-<0.11
NGC 6440	4.5×10^{-13}	0.5-4.5	7.9	EX $kT = 5$ keV	3	0.005
GS 2000 + 25	$< 8.8 - < 5.6 \times 10^{-12}$	1.2-37.1	1.0	PL $0.5 \leq \alpha \leq 1.5$	4	<0.08-<0.35
GS 2023 + 338	2.6×10^{-11}	1.2-37.	3.2	PL $\alpha = 0.43$	4	0.13
A 0620 − 00	$< 2.3 \times 10^{-12}$	0.15-4.5	0.0	BB $kT = 1$ keV	5	< 0.05

used do not correctly represent the source spectrum. Cen X-4 is so far the only soft X-ray transient unambiguously detected in quiescence, at a luminosity $L_x \sim 4.3 - 8.0 \times 10^{32}$ erg s^{-1} (for a distance d = 1.2 kpc; Chevalier et al. 1989). An upper limit at a comparable level was obtained with GINGA (Kulkarni et al. 1992). Aql X-1 probably also has been detected in quiescence, at $L_x \sim 2.4 \times 10^{34}$ erg s^{-1} (d = 2.5 kpc), but positional inaccuracy of the source precludes certain identification with Aql X-1 (Czerny et al. 1987); another observation of Aql X-1 set a 3-σ upper limit at $L_x < 2.2 \times 10^{33}$ erg s^{-1} (van Paradijs et al. 1987). The low-luminosity source detected in the globular cluster NGC 6440 at $L_x \simeq 4.3 \times 10^{32}$ erg s^{-1} (for d = 3.5 kpc) possibly is the same object as the bright transient observed earlier near the same cluster (Hertz & Grindlay 1983). As globular clusters are now known to contain multiple dim sources (e.g. NGC 6397, Cool et al 1993; 47 Tuc, Verbunt et al. 1993; Hasinger et al. 1994) the identification is not certain, however. And finally, GS 2023 + 338 may have been detected at $L_x \simeq 6.0 \times 10^{33}$ erg s^{-1} (for d = 3.5 kpc), but once more, positional uncertainty precludes certain identification (Mineshige et al. 1992).

The detection with EXOSAT of Cen X-4 was made with the low-energy telescope, which does not provide spectral information (van Paradijs et al. 1987). Czerny et al. (1987) fit a bremsstrahlung spectrum to their possible detection of Aql X-1 in quiescence and find a temperature range of 2.1–3.9 keV; a powerlaw fit to the same spectrum give an energy flux index between 1.2 and 1.9.

In this article we discuss ROSAT observations of four transients, Aql X-1, GS 2000 + 25, GS 2023 + 338 and H 1705 − 25. Aql X-1 has shown X-ray bursts, and thus is a neutron star (Koyama et al. 1981). The mass function of the optical counterpart of GS 2023 + 338 indicates that the compact object is a black hole (Casares et al. 1992). GS 2000 + 25 and H 1705 − 25 may harbour black holes, as their X-ray spectra are similar to those of confirmed black holes like A 0620 − 00 (Tsunemi et al. 1989; White et al. 1984).

We planned our ROSAT observations with several goals in mind. First, we hoped to detect, or set upper limits to, the flux in quiescence at lower flux levels than hitherto possible. Second, in case of a detection, we wished to establish whether the low quiescent X-ray flux is indeed a consequence not only of lower accretion rate, but also of a lower characteristic temperature, as suggested by Eq. 2. In the case of Aql X-1 and GS 2023 + 338 a more accurate position would allow confirmation that the sources seen by EINSTEIN and GINGA are indeed the transients, and not unrelated objects. And finally, we intended to look for pulsations at low flux levels, for the following reason.

It is currently thought that at least some low-mass X-ray binaries with a neutron star evolve into binaries in which a low-mass degenerate star accompanies a radio pulsar. This implies that the neutron star has a magnetic field $B \gtrsim 10^8$ G. If this field disrupts the accretion disk at some distance from the neutron star surface, one would expect the X-ray flux to be modulated at the rotation period of the neutron star. Searches for X-ray pulsations in low-mass X-ray binaries in which the neutron star does not have a field $B \gtrsim 10^{12}$ G have so far been unsuccessful, with two exceptions. A periodicity at 7.6 Hz was found during a burst in Aql X-1 (Schoelkopf & Kelley 1991). And a periodicity at 220 Hz was found to be present for a $\sim$ 1 hr interval in the X-ray flux of Sco X-1; as the observed frequency appears unaffected by the orbital motion of the neutron star, it may be spurious, despite its apparent high significance (Middleditch & Priedhorsky 1986). At the low accretion rate of a transient in quiescence the magnetic field of the neutron star may be able to disrupt the accretion disk more efficiently, which could lead to a more pronounced pulse profile.

In Sect. 2 we discuss the observations that we obtained and the data analysis. Our results are described in Sect. 3, and some of their implications are discussed in Sect. 4.

2. Observations

Aql X-1 was observed with the X-ray telescope on board of ROSAT on five occasions, four times with the Position Sensitive Proportional Counter (PSPC), and once with the High Resolution Imager (HRI). Descriptions of satellite and instruments can be found in Trümper (1983) and Pfeffermann et al. (1986). The first of the PSPC observations was that of the All–Sky Survey, and consists of 23 scans. (A general description of the All–Sky Survey is given by Voges 1992). The other four observations of Aql X-1 are pointed observations; one of these was actually aimed at the globular cluster NGC 6760, and contains Aql X-1 as an off–center serendipitous source.

GS 2000+25 was observed during two pointed observations with the X-ray telescope combined with the PSPC, and H 1705−25 was observed in a single pointed observation with the HRI. To these observations we add the data at the position of GS 2023+338 from the All Sky Survey. A log of the observations is given in Table 2.

For the PSPC data of Aql X-1, we extracted the data from a circle centered on the source, and determined the background from a ring well outside this circle. In the case of the 1992 March observations, the source was so bright that a ring could not be used; instead background photons were extracted from a circle at the far edge of the detector. In this observation the background rate is so low compared to the source countrate ($0.2\,\mathrm{s}^{-1}$ compared to $140\,\mathrm{s}^{-1}$) that background subtraction makes little difference. The radius of the source extraction was $68''$ for the 1992 October observation, when the source was quiescent, and $450''$ for the 1992 March off–centered observation. For the HRI data the source extraction radius was $36''$ and the inner and outer radii of the background ring $80''$ and $156''$, respectively. The Survey observation has been analyzed following the procedures reported in Belloni et al. (1993). The background photons were normalized to the same area as that of the source extraction circle, and subtracted. The resulting countrates are given in Table 2.

The PSPC observations of GS 2000 + 25 have long exposures, and show quite a few point sources. At the position of the transient however, no source is found. To determine the background, a rectangular box was used which is free of point sources, and from this a background count number (corrected for vignetting) is determined in a circle with 90 arcsec radius, during the full observation. The 4-σ upper limits to a source in this circle are 22.1 counts in channels 10–240, and 11.4 counts in channels 41–240, during the 12 685 s exposure. The limits are 13.4 counts and 7.6 counts, respectively, during the 6 985 s exposure. The upper limits in channels 41–240 are more stringent, because the background in these channels is much lower than in channels 10–40. (An illustration of this higher background at lower energies may be seen in the observation of Aql X-1, shown in Fig. 1). In the HRI pointing of H 1705 − 25 no source was detected at the position of the transient. We estimate that a source of 10 cts would have been detected at a 4-σ level of confidence, and list the corresponding upper limit to the count rate in Table 2.

The Survey data for GS 2023 + 338 have been analyzed following the procedures reported in Belloni et al. (1993). This source was detected, and the resulting countrate is listed in Table 2. The position of the detected source is $\alpha(2000) = 20^{\mathrm{h}}24^{\mathrm{m}}05.4^{s}$, $\delta(2000) = 33°52'01''$ with an uncertainty of $\sim 25''$, and thus compatible with the source position for GS 2023+338 given by Wagner et al. (1991). There is no other source within $25'$ from this source. We conclude that the detected source is indeed GS 2023 + 338.

3. Results

3.1. Spectra of Aql X-1

To obtain the spectrum of Aql X-1, we rebinned the 256 energy channels of the PSPC data so that oversampling is maximally 3 times the energy resolution. Channels 1 to 9 and 246 to 250 have been ignored, as the detector sensitivity in these is low and not well determined. This yielded spectra with 18 energy bins. To these binned data we fit various spectra. For each type of spectrum investigated, i.e. blackbody, thermal bremsstrahlung, and powerlaw, we first fit the data with the highest countrate, viz. the March 1992 data. For these fits we include the column density in the parameters to be fitted. The accuracy with which the countrate can be determined in the March 1992 data is such that uncertainty in the PSPC calibration may affect the fit. In fitting these data, we therefore add 2% of the observed countrate to the uncertainty in the countrate, in quadrature, to mimic a 2% uncertainty in the calibration. In fitting the data at lower countrates of the remaining observations, we fix the column density at the value found for the March 1993 data. The results are summarized in Table 3. The blackbody fits are shown in Fig. 1.

The fluxes observed in 1990 October and 1992 March differ by a factor ten, but the spectra are the same, within the errors. The reduced χ^2 of the March 1992 data is 3.8. We conclude that a single–component spectrum does not describe the observed spectrum well. The observed spectrum is harder than a single–component spectrum is able to reproduce. In the 1992 October observation the countrate is a factor 4000 below the flux in 1992 March, and the spectrum is significantly softer, having a black-body temperature roughly half that of the bright spectrum. The same temperature was found for the 1993 March spectrum, also at a fairly low countrate. Thus, the temperature does drop somewhat as the luminosity of Aql X-1 decreases, but not nearly as much as expected on the basis of Eq. 2 for a constant emission area.

The pulse-height distribution of the HRI is compatible with that expected for a spectrum with the same form as we observe in the PSPC in October 1992 and March 1993. Assuming a

Table 2. Observation log of the ROSAT observations of soft X-ray transients discussed in this paper, giving the Julian date of the beginning and end of each observation, the effective exposure time (corrected for vignetting), the number of separate pointings (number of scans for All-Sky Survey data), and the average countrate of the source. The PSPC countrates refer to channels 10–245 for Aql X-1, and to channels 41–240 for the other sources.

date,UT (start)		date,UT (end)		$t_{\rm exp}$(s)	n	ct-rate		remarks
		Aql X-1						
1990 Sep 28	18:24	Oct 7	03:27	477	23	14.8±0.2	PSPC	All–Sky Survey
1991 Mar 24	03:18	Mar 24	05:39	5154	3	0.016±0.002	HRI	
1992 Mar 24	05:42	Mar 24	09:05	1601	3	141.9±0.4	PSPC	serendipitous
1992 Oct 15	13:19	Oct 17	05:28	14359	10	0.030±0.002	PSPC	
1993 Mar 24	04:41	Mar 26	10:10	12555	10	0.055±0.002	PSPC	
		GS 2000 + 25						
1992 May 1	13:23	May 7	13:12	12685	13	<0.0009 (4σ)	PSPC	
1993 Apr 9	06:42	Apr 11	13:13	6985	6	<0.0011 (4σ)	PSPC	
		H 1705 − 25						
1991 Mar 19	11:14	Mar 20	11:40	1717	2	<0.006 (4σ)	HRI	
		GS 2023 + 338						
1990 Nov 2	18:42	Nov 5	13:57	958	43	0.028±0.009	PSPC	All–Sky Survey

Table 3. Fits to data of Aql X-1, with their χ^2 per degree of freedom, and resulting fluxes and luminosities (for assumed distance of 2.5 kpc) in the ROSAT band, i.e. between 0.4 and 2.4 keV. For the blackbody fits we also give the fraction of the bolometric luminosity emitted in this band. The column density is one of the free parameters for fits to the March 1992 observation, but kept fixed for the other fits. The number of degrees of freedom is thus 15 for the March 1992 data, and 16 for the other PSPC data. The temperature for the March 1991 HRI observation is assumed.

spectrum		$N_{\rm H}$ (10^{21} cm^{-2})	${\chi_\nu}^2$	$F_{\rm x}(0.4-2.4\,{\rm keV})$ erg cm^{-2} s^{-1}	$L_{\rm x}$ erg s^{-1}	$L_{\rm x}/L_{\rm bol}$
	October 1990					
blackbody	$kT = 0.55 \pm 0.03$ keV	2.1	1.8	3.3×10^{-10}	2.5×10^{35}	0.65
bremsstrahlung	$kT \gtrsim 5$ keV	4.0	1.7	5.0×10^{-10}	3.7×10^{35}	
powerlaw	$\alpha = 0.37 \pm 0.10$	4.1	1.6	5.1×10^{-10}	3.8×10^{35}	
	March 1991					
blackbody	$kT = 0.31$ keV	2.1	–	8.2×10^{-13}	6.1×10^{32}	0.89
	March 1992					
blackbody	$kT = 0.55 \pm 0.02$ keV	2.1 ± 0.2	3.8	3.2×10^{-9}	2.4×10^{36}	0.65
bremsstrahlung	$kT = 14.8 \pm 8.9$ keV	4.0 ± 2.3	3.2	4.9×10^{-9}	3.6×10^{36}	
powerlaw	$\alpha = 0.40 \pm 0.14$	4.1±0.1	3.2	5.0×10^{-9}	3.7×10^{36}	
	October 1992					
blackbody	$kT = 0.31 \pm 0.03$ keV	2.1	0.9	5.9×10^{-13}	4.4×10^{32}	0.89
bremsstrahlung	$kT = 0.80 \pm 0.18$ keV	4.0	0.9	11.7×10^{-13}	8.7×10^{32}	
powerlaw	$\alpha = 1.75 \pm 0.3$	4.1	1.1	13.6×10^{-13}	10.2×10^{32}	
	March 1993					
blackbody	$kT = 0.30 \pm 0.02$ keV	2.1	0.8	1.1×10^{-12}	8.2×10^{32}	0.89
bremsstrahlung	$kT = 0.77 \pm 0.13$ keV	4.0	0.8	2.2×10^{-12}	16.5×10^{32}	
powerlaw	$\alpha = 1.8 \pm 0.2$	4.1	1.1	2.7×10^{-12}	20.0×10^{32}	

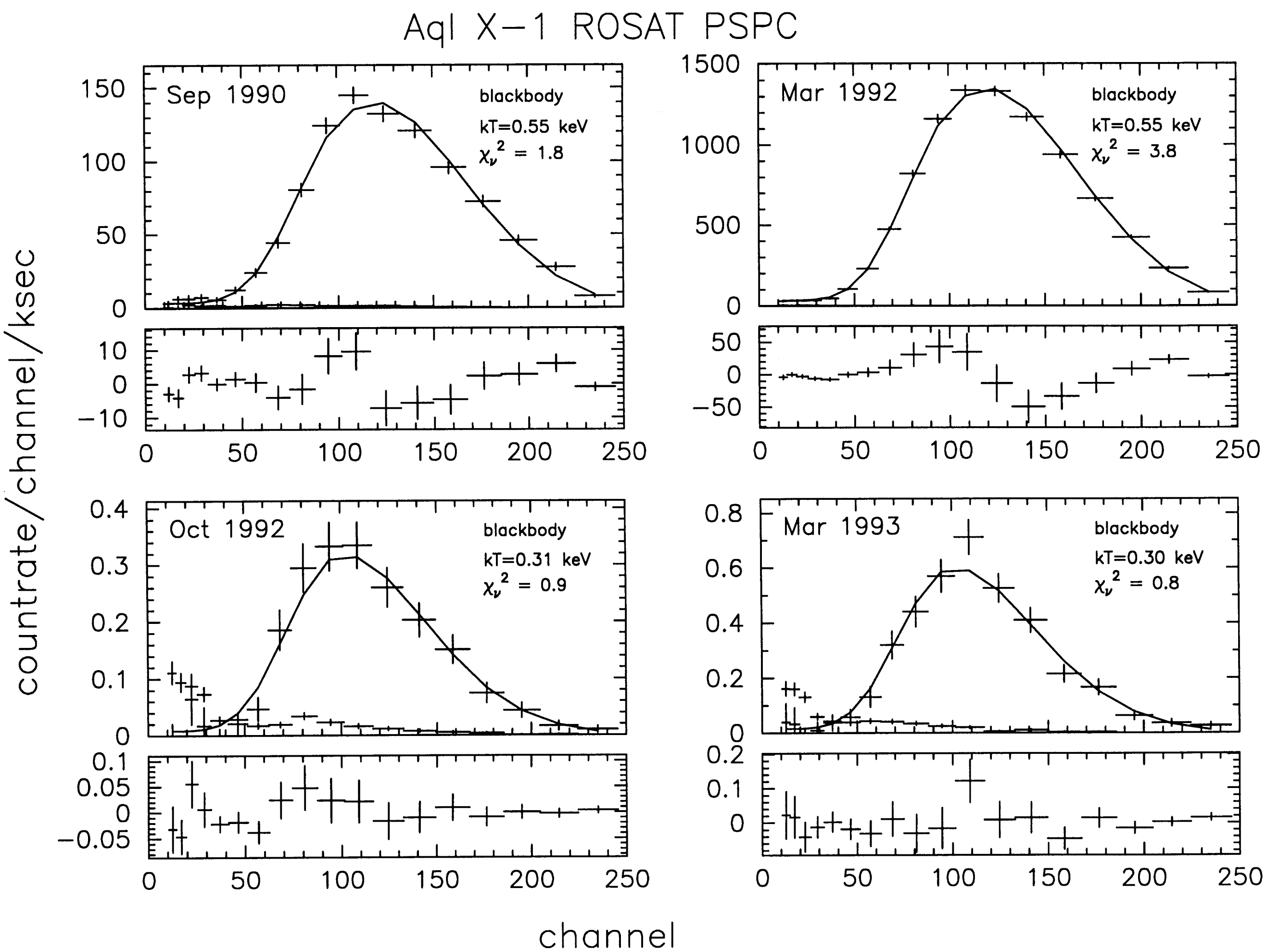

Fig. 1. Blackbody fits to the ROSAT PSPC data of Aql X-1. Each graph shows the observed source and background countrates, together with the fitted source countrates (upper panel) and the difference between observed and calculated countrates (lower panel). Channel n corresponds roughly to a photon energy of $n \times 0.01$ keV. In September 1990 and March 1992 the background countrates are negligible; during the October 1992 and March 1993 observations the background countrates dominate in the channels 10-40.

$kT = 0.31$ keV blackbody spectrum at the source, we obtain from the observed HRI countrate an unabsorbed flux at Earth between 0.4 and 2.4 keV of 8.2×10^{-13} erg cm^{-2} s^{-1}.

3.2. Periodicity search in Aql X-1

We performed periodicity searches in the data obtained during the three pointed observations of Aql X-1, in order to look for possible pulsations from the neutron star. In doing so, we took account of the orbital motion of the neutron star, which will induce shifts in the frequency of a periodic signal. Using the 19 hr orbital period (Chevalier & Ilovaisky 1991) and assuming a mass of 1.4 $M_\odot$ for the neutron star and $\lesssim 0.8\,M_\odot$ for the companion, we find that shifts larger than one frequency resolution element in a Fourier transform can be induced for data segments longer than about 170 s if the pulse frequency is 1000 Hz, and 600 s if it is 100 Hz. For a pulsar with a 7.6 Hz pulse frequency (see Introduction), coherence can be lost in about 2000 s. Acceleration searches such as previously discussed by, e.g. , Wood et al. (1991), and Johnston & Kulkarni (1990), could improve these limiting time segment lengths (up to $\simeq$ 6000 s), but would produce only a modest improvement in the sensitivity to pulsations because of the fragmented nature of the data (caused by the low Earth orbit of ROSAT). The longest contiguous segment in our data is only 3000 s (at a raw count rate of 0.06 cts/s); the longest segment during the outburst (raw count rate 100 cts/s) is 600 s. Therefore, we decided to perform unaccelerated searches on data segments sufficiently short to prevent loss of coherence.

We divided the outburst data into 11 segments of 128 s and binned the data to a time resolution of $\simeq$ 0.5 msec to search for pulsations in the 128–1024 Hz range, and also into 3 segments of 512 s at a time resolution of $\simeq$ 4 ms to search the 1–128 Hz range. No pulsations were detected in any of the segments over the 3 σ detection threshold (which we set taking into account the number of trials). 90% confidence upper limits (set according to van der Klis 1989 but using the power distribution described by Groth 1975) to the amplitude of a sinusoidal modulation varied between 6.2 and 7.2% for modulation frequencies between 128 and 1024 Hz, and between 2.7 and 3.0% between 1 and 128 Hz (close to the Nyquist frequencies these numbers are worse by a factor of about 1.5). We independently searched the outburst data for evidence of the 7.595 Hz frequency reported by Schoelkopf & Kelley (1991). As the orbital velocity of the neutron star under the assumptions made above is $\lesssim 10^7$cm s^{-1}, this frequency, if it is a neutron star pulse frequency, could only shift by $\simeq$ 0.01 Hz due to the orbital motion. We searched the frequency interval 7.585–7.605 Hz for significant excesses; none were found. 90% confidence upper limits were between 1.1 and 1.5%.

The count rates of the quiescent data are too low to allow a search for a millisecond pulsar. We did, however, perform a search for the 7.6 Hz modulation in a similar manner as described for the outburst data. For this purpose, we used the six longest contiguous data segments, which had raw count rates that varied between 0.04 and 0.06 cts/s and lengths between 3000 and 1300 s. No signal was detected. 90% confidence upper limits on the pulse amplitude were between 26 and 45%.

3.3. *Upper limits for H 1705 − 25 and GS 2000 + 25*

The conversion of an upper limit in the countrate to an upper limit in flux depends on the assumed spectrum. To illustrate this we calculated fluxes in the bandpass 0.4-2.4 keV for a variety of assumed spectral parameters. The results are illustrated in Table 4. Our examples show that the flux between 0.4-2.4 keV varies by less than a factor two for a wide variety of assumed spectral parameters. Only very soft spectra, easily absorbed, require much higher fluxes to produce the same countrates.

Many soft X-ray transients show a spectrum that combines a soft blackbody with a harder power law component (see e.g. Tanaka & Lewin 1994). At lower flux levels the power law component becomes the dominant one. The powerlaw models in the Table therefore may be the more relevant ones.

The upper limit to the flux in the range 1.2 − 37.1 keV of GS 2000 + 25 obtained by Mineshige et al. (1992) with GINGA (see Table 1) may be converted to a limit of 1.6 − 7.0 $\times 10^{-12}$ erg cm^{-2} s^{-1} to the flux between 0.4 − 2.4 keV. From Table 4 we see that our upper limit is about two orders of magnitude below the upper limit obtained with GINGA, if the spectrum is a powerlaw. For an assumed distance of 2 kpc our limit of $\sim 2 \times 10^{-14}$ erg cm^{-2} s^{-1} translates into a luminosity limit of 0.96×10^{31} erg s^{-1}.

For the outburst spectrum of H 1705 − 25 Griffiths et al. (1978) use a photon spectrum $N_\nu \propto E^{-1.4} \exp^{-E/kT}$ with a temperature kT = 3 keV and a column $N_{\rm H} = 3 \times 10^{21}$ cm^{-2} (the factor $E^{-1.4}$ is an approximated Gaunt factor). For the same spectrum our upper limit in the HRI instrument leads to an unabsorbed flux limit between 0.4 and 2.4 keV of 4.5×10^{-13} erg cm^{-2} s^{-1}, corresponding to a luminosity of $\sim 4.9 \times 10^{32}$ erg s^{-1} at an assumed distance of 3 kpc. For a powerlaw spectrum with energy flux index 0.0 the obtained flux and luminosity limits are the same within 2% .

3.4. *GS 2023 + 338*

GS 2023 + 338 is clearly detected in the All–Sky Survey, at a countrate of 0.028±0.009 cts/s in channels 11-240. For a variety of assumed spectra, the observed countrate corresponds to an unabsorbed flux between 0.4 − 2.4 keV of $\sim 10^{-12}$ erg cm^{-2} s^{-1} (see Table 4), which for a distance of 3.5 kpc translates into a luminosity in the same band of $\sim 1.5 \times 10^{33}$ erg s^{-1}. Mineshige et al. (1992) fit a powerlaw spectrum to their detection with GINGA (see Table 1). Their fit predicts a countrate in the ROSAT PSPC of 0.13 cts/s, a factor $\sim 4 - 5$ above the countrate that we observed. This may well be due to variability of the source. (Mineshige et al. note that the source must have varied during the GINGA observation to explain the offset between the GINGA source posititon and the known position of GS2023+338.) Alternatively, the source may be harder or more absorbed than assumed by Mineshige et al. (1992).

4. Discussion

We have detected Aql X-1 and GS 2023 + 338 at low flux levels, whereas we only find upper limits for GS 2000 + 25 and H 1705 − 25. If we add these results to previous observations that were sensitive enough to detect sources at the $\sim 10^{33}$ erg s^{-1} level, we find that two transients containing a neutron star, Cen X-4 and Aql X-1, and one transient containing a black hole, GS 2023 + 338, have been detected in quiescence, whereas only upper limits were obtained for three transients that (possibly) contain black holes, A 0620−00, GS 2000+25 and H 1705−25.

As mentioned in the introduction, possible detections of Aql X-1 and GS 2023 + 338 have been reported previously, but in both cases uncertain positions precluded certain identification. In view of our results we think it is likely that both detections were indeed of the transients in their quiescent state. The source in the direction of Aql X-1 has a flux level of $\sim 2 \times 10^{-11}$ erg cm^{-2} s^{-1}, and its spectrum fits a powerlaw with energy flux index α = 1.5 (Czerny et al. 1987). Both flux level and powerlaw index lie between the values for the ROSAT detections of October 1990 and March 1993. The absence of other sources near Aql X-1 at these flux levels in any of our five observations indicates that the EINSTEIN source may indeed be Aql X-1.

The flux level of the source seen in the direction of GS 2023+338 with GINGA is higher than the level detected with ROSAT. No other source is detected by us near GS 2023 + 338, and we conclude that the source detected by GINGA probably is the transient. Its off-set position in the GINGA observation must then be due to variability during the observation.

Table 4. The unabsorbed flux at Earth between 0.4 – 2.4 keV calculated for a variety of assumed spectral parameters and absorption columns. For GS 2000 + 25 the fluxes are 4-σ upper limits calculated from the upper limit to the countrate determined for the May 1992 observation. For GS 2023 + 338 the fluxes are calculated for the observed countrate.

GS 2000 + 25; $N_{\rm H} = 1.0 - 2.0 \times 10^{21}$ cm^{-2}					
powerlaw		blackbody		bremsstrahlung	
α	$f_{\rm x}$(erg cm^{-2} s^{-1})	kT	$f_{\rm x}$(erg cm^{-2} s^{-1})	kT	$f_{\rm x}$(erg cm^{-2} s^{-1})
0.5	$1.7 - 2.2 \times 10^{-14}$	2.0	$2.3 - 2.7 \times 10^{-14}$	2.0	$1.6 - 2.1 \times 10^{-14}$
1.0	$1.7 - 2.2 \times 10^{-14}$	0.5	$1.6 - 2.0 \times 10^{-14}$	0.5	$1.8 - 2.5 \times 10^{-14}$
1.5	$1.8 - 2.4 \times 10^{-14}$	0.1	$2.9 - 4.9 \times 10^{-14}$	0.1	$5.1 - 11. \times 10^{-14}$
GS 2023 + 338; $N_{\rm H} = 3.2 - 6.0 \times 10^{21}$ cm^{-2}					
powerlaw		blackbody		bremsstrahlung	
α	$f_{\rm x}$(erg cm^{-2} s^{-1})	kT	$f_{\rm x}$(erg cm^{-2} s^{-1})	kT	$f_{\rm x}$(erg cm^{-2} s^{-1})
0.0	$8.4 - 13. \times 10^{-13}$	2.0	$9.6 - 13. \times 10^{-13}$	2.0	$8.5 - 14. \times 10^{-13}$
0.43	$8.5 - 13. \times 10^{-13}$	0.5	$7.4 - 11. \times 10^{-13}$	0.5	$11. - 21. \times 10^{-13}$
1.0	$9.1 - 15. \times 10^{-13}$	0.1	$27. - 80. \times 10^{-13}$	0.1	$74. - 330 \times 10^{-13}$

The luminosity of an accreting black hole must of necessity come from the accretion disk, in contrast to the luminosity of an accreting neutron star, where the neutron–star surface may contribute. Our detection of GS 2023 + 338 shows that accretion onto a black hole may continue at a very low level. The luminosity observed with ROSAT is a factor $\sim 10^5$ below the source luminosity at outburst maximum. The sensitive upper limits to A 0620 – 00, GS 2000 + 25 and H 1705 – 25 show that the accretion can drop to an even lower level in some cases.

It is interesting that during most observations of Aql X-1 and Cen X-4 sufficiently sensitive to detect these sources at luminosities $\sim 10^{33}$ erg s^{-1}, detections were obtained: Cen X-4 was detected with EINSTEIN and with EXOSAT, Aql X-1 with EINSTEIN, and now on several occasions with ROSAT. If the spectrum of Cen X-4 in quiescence is similar to that of Aql X-1, its softness could explain the failure of GINGA to detect Cen X-4 (Kulkarni et al. 1992). The ROSAT detections of Aql X-1 at the lowest flux levels lie below the upper limit found with EXOSAT (see Tables 1,2). The upper limits to the X-ray luminosities of A 0620 – 00 (corresponding to $\lesssim 4 \times 10^{31}$ erg s^{-1} between 0.4-2.4 keV, see Table 1) and to GS 2000+25 ($\lesssim 10^{31}$ erg s^{-1}) are an order of magnitude or more below the lowest X-ray luminosities of Cen X-4 and Aql X-1. It is possible that the spectrum of the disk around a black hole is softer, due to the higher mass of the compact object, than that around a neutron star (Tanaka & Lewin 1994). Alternatively, it may be that the contribution by the surface of the neutron star becomes important at very low levels of accretion.

The detections in quiescence of GS 2023+338 with GINGA and ROSAT did not provide enough counts to determine the spectrum. The flux level at quiescence is a factor $10^5 - 10^6$ below the maximum level of the outburst. We cannot exclude a significant drop in temperature, in accordance with Eqs.(1,2), for this source. In any case, the low flux level observed for GS 2023 + 338 is lower than required in models in which the outbursts of soft X-ray transients are triggered by irradiation of the donor star during quiescence (Hameury et al. 1986), as already pointed out on the basis of the GINGA observations (Mineshige et al. 1992).

EINSTEIN MPC spectra of Aql X-1 between 1.2 and 20 keV, obtained during the outburst, can be fitted with simple bremsstrahlung models with temperature 5–6 keV (Czerny et al. 1987). Our ROSAT observation of March 1992 is obtained at a similar luminosity, but cannot be fitted with a single bremsstrahlung model, and requires a second component for the low–energy flux. At a flux level between those of our September 1990 and March 1993 ROSAT observations, the EINSTEIN MPC data were described with a powerlaw of slope 1.5 (Czerny et al. 1987). This is compatible with the trend toward softer spectra at lower luminosities that we observe in the ROSAT data.

The ROSAT data do not support the possibility that the X-ray luminosity of Aql X-1 declines mainly due to a decrease in the temperature, but require a precipitous drop in flux also at energies around 0.1 keV. This indicates that the accretion rate onto the neutron star drops by many orders of magnitude in quiescence. At outburst maximum, the luminosity of Aql X-1 is $L_{\rm x} \simeq 3 \times 10^{37}$ erg s^{-1} (van Paradijs & Verbunt 1984), which according to Eq. 1 corresponds to an accretion rate $\dot{M} \simeq 2 \times 10^{17}$ g/s. The blackbody fits to the spectra and countrates of Aql X-1 imply a lowest observed luminosity $L_{\rm bol} \simeq 5 \times 10^{32}$ erg s^{-1}, which according to Eq. 1 implies an accretion rate $\dot{M} \simeq 3 \times 10^{12}$ g/s, Note that the ratio of accretion rates at maximum and minimum does not depend on the distance to Aql X-1 (here assumed to be 2.5 kpc), even though the absolute values do.

If the surface of the neutron star becomes a main contributor to the flux at a luminosity $\sim 10^{33}$ erg s^{-1}, we would expect the X-ray spectrum to be that of an optically thick atmosphere. The spectrum of a neutron star atmosphere is not a blackbody, but its flux distribution resembles that of a blackbody with a temperature proportional to, but not necessarily equal to, the effective temperature $T_{\rm eff}$ corresponding to the emitted bolometric flux (London et al. 1986). For $T_{\rm eff} < 1$ keV, the proportionality constant is close to unity. Our ROSAT data are compatible with such a spectrum at $L_{\rm x} \sim 10^{33}$ erg s^{-1}. The low flux levels that we observe would then suggest that in quiescence only a fraction of the neutron star surface is emitting. For example, at a luminosity of 5×10^{32} erg s^{-1} an effective temperature $T_{\rm eff} = T_{\rm bb} \simeq 0.3$ keV implies a radiating surface of order 1 km^2.

The small surface area may be due to funneling of the accretion by a magnetic field, or to domination of the flux emission by a boundary layer between disk and neutron star. Both of these explanations would require that accretion is continuing, at a low level, during quiescence. van Paradijs et al. (1987) already argued on the basis of an increase in the flux of Cen X-4 during quiescence that accretion continues in quiescence. The absence of detected pulsations would argue for a boundary layer rather than for a hot spot, and therefore would imply a very low magnetic field for the neutron star.

As remarked by Kulkarni et al. (1992) observations of soft X-ray transients in quiescence may be used to constrain the surface magnetic field strength B and the rotation period P of the neutron star. For example, it may be assumed that the neutron star will switch on as a radio pulsar, if the radius r_m of its magnetosphere becomes larger than the radius l_c of the light cylinder. Conversely, if no radio emission is emitted, this implies $l_c \gtrsim r_m$ or

$$P \gtrsim f \frac{2\pi}{c} B^{4/7} R^{12/7} \dot{M}^{-2/7} (GM)^{-1/7} \simeq 0.019\,{\rm s} f B_9{}^{4/7} \dot{M}_{13}^{-2/7} \quad (3)$$

where f is a factor of order unity, which depends on the assumptions made in estimating the magnetospheric radius (see, e.g. Verbunt 1990); it should also be noted that the assumption of a dipole magnetic field breaks down at radii comparable to the light cylinder), and where B_9 and $\dot{M}_{13}$ are the field strength in units of 10^9 G and the accretion rate in units of 10^{13}g/s. Eq.2 of Kulkarni et al. (1992) is identical to our Eq.3 for $f \simeq 0.9$. Noting that X-rays of Cen X-4 were still observed, i.e. accretion still occurring, at $\dot{M} \simeq 2 \times 10^{13}$g/s (see Table 1), Kulkarni et al. (1992) use their deep upper limit to any radio emission of Cen X-4, to argue that its pulse period must be longer than 0.013 s for $B = 10^9$ G. For a field $B = 2 \times 10^8$ G, the period limit drops to 0.005 s. (These estimates assume a neutron star of 1.4 $M_\odot$ with a radius of 10 km.)

We will show, however, that a more stringent limit may be derived from accretion at low levels, detected in X-rays. Matter can accrete onto the neutron star, if the radius of the magnetosphere is smaller than the corotation radius, the radius at which the frequency of a circular orbit equals the rotation frequency of the neutron star (Illarionov & Sunyaev 1975). This condition may be written $r_m \lesssim (P/2\pi)^{2/3}(GM)^{1/3}$ or

$$P \gtrsim f^{3/2} 2\pi B^{6/7} R^{18/7} \dot{M}^{-3/7} (GM)^{-5/7} \simeq 0.40\,{\rm s} f^{3/2} B_9{}^{6/7} \dot{M}_{13}^{-3/7} \quad (4)$$

For $\dot{M} = 2 \times 10^{13}$g/s and $f \simeq 0.9$ we thus find $P \gtrsim 0.26\,{\rm s} B_9{}^{6/7}$ for Cen X-4, a much more stringent limit than the one derived from the absence of radio flux.

Our deepest detection of Aql X-1 corresponds to an accretion rate $\dot{M} \simeq 3 \times 10^{12}$g/s, so that Eq.4 sets a limit to the rotation period of the neutron star at $P \gtrsim 0.6\,{\rm s} B_9{}^{6/7}$. This is compatible with the period detected by Schoelkopf & Kelley (1991), only if the magnetic field of the neutron star in Aql X-1 is close to or below the lowest value observed in millisecond radio pulsars.

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