

GX 349+2 (Sco X-2): an odd-ball among the Z sources

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Abstract. We report on about 4 hrs of observations made with the Rossi X-ray Timing Explorer on 1997 May 2 of the low-mass X-ray binary and Z source GX 349+2 (Sco X-2). Initially the source was in the normal branch (NB), later it moved to the flaring branch (FB). In the NB the power spectra reveal a broad (FWHM \sim 16 Hz) noise component peaking near 9 Hz, with a fractional rms amplitude of \sim 3% (2–30 keV). This noise component does not resemble the strong quasi-periodic oscillations (QPO) usually seen in the NB of other Z sources. We set 95% confidence upper limits on the fractional rms of \sim 0.9% (2–30 keV) on any such QPO. In the FB the power spectrum showed a somewhat less broad noise component (FWHM \sim 11 Hz) peaking near 6 Hz with a fractional rms of \sim 4% (2–30 keV). We compare our results with previous reports, and find that the fast timing behaviour changes not only with position in the Z, but also as a function of the position of the Z track in the hardness-intensity diagram. By comparing GX 349+2 with the other Z and atoll sources, we conclude that GX 349+2 differs from the Z sources in various aspects and shows similarities to the behaviour seen in the bright atoll sources, such as GX 13+1 and GX 3+1. We also searched for kilo-Hertz QPO, similar to those present in other Z sources. We only found weak evidence (2.6σ confidence) for a QPO near 1020 Hz with FWHM \sim 40 Hz and fractional rms of \sim 1%. We note that this frequency and fractional rms are consistent with those expected and observed in the lower NB/FB of the Z sources Sco X-1, GX 17+2 and Cyg X-2.

Key words: accretion, accretion disks – binaries: close – stars: individual (GX 349+2, Sco X-2) – stars: neutron – X-rays: stars

1. Introduction

The group of the Z sources consists of 6 bright low-mass X-ray binaries (LMXBs): Sco X-1, GX 5–1, GX 349+2 (or Sco X-2), GX 17+2, GX 340+0 and Cyg X-2 (Hasinger & van der Klis 1989, van der Klis 1995b). GX 349+2 was classified as a Z source based on its narrow branches in the X-ray color-color diagram (CD) and its steep very-low-frequency (\lesssim 1 Hz) noise slope. The Z sources trace out Z-like shaped tracks in the CD, with the limbs of the Z called horizontal branch (HB), normal

branch (NB) and flaring branch (FB). It is thought that mass accretion rate, \dot{M} , increases from the HB, through the NB, to the FB. All the six sources have displayed the three branches, except for GX 349+2 which has up to now only been seen in the NB and FB (see Hasinger & van der Klis 1989; Kuulkers & van der Klis 1995a).

The fast time variability is closely related to position in the Z. In the HB and upper part of the NB quasi-periodic oscillations (QPO) are present with frequencies between \sim 15–60 Hz (HBO) together with a noise component below \lesssim 20 Hz (called low-frequency noise, LFN). On the NB a different QPO (NBO) is present with frequencies between 5–7 Hz, FWHM between 2–4 Hz and fractional rms of 1–4% (\sim 2–10 keV). On the lower part of the FB in Sco X-1 and GX 17+2 the NBO merge smoothly into FB QPO (FBO) with frequencies of up to \sim 20 Hz.

All Z sources show shifts in the position of the Z track in the hardness-intensity diagram (HID). Only in Cyg X-2, GX 5–1, and GX 340+0 have these been observed to be accompanied by Z-track shifts and morphology changes in the CD (see Kuulkers & van der Klis 1995a). In the case of GX 349+2, two EXOSAT observations showed two tracks shifted in intensity in the HID, and we therefore refer to these two tracks as the Z observed at “low overall intensities” and “high overall intensities”.

Recently, the Rossi X-ray Timing Explorer (RXTE) has proven to be a gold mine for the detection of kHz QPO in LMXBs (e.g. van der Klis 1997, and references therein). So far, kHz QPO in Z sources have been found in Sco X-1, GX 5–1, GX 17+2 and Cyg X-2 (van der Klis et al. 1996a,b, 1997a,b, Wijnands et al. 1997b, 1998). The frequency of the kHz QPO increases with increasing \dot{M} .

GX 349+2 is a poorly studied Z source. Therefore, much of the properties inferred from the other Z sources have been assumed to apply also for GX 349+2. In this paper we report on observations of GX 349+2 as observed with the RXTE PCA, compare them with previous observations, and show that the fast time variability is somewhat different from that observed in the other Z sources.

2. Observations and analysis

The RXTE PCA (Bradt et al. 1993) observed GX 349+2 on 1997 May 2 18:44–22:54 UTC. The data were collected from all five proportional counter units (PCUs) with a time resolution

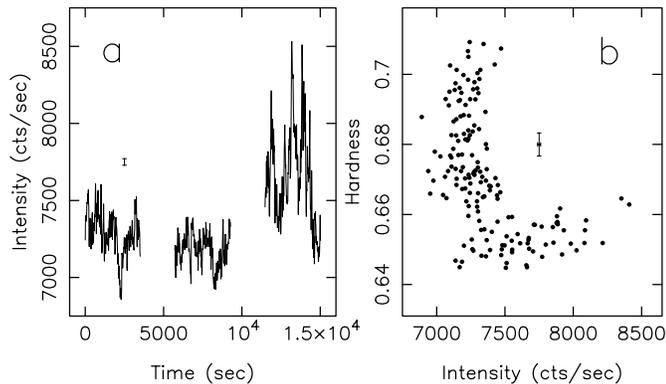


Fig. 1. **a** Light curve and **b** hardness-intensity diagram (HID) of GX 349+2. The intensity is the source count rate in the 2.0–19.7 keV energy range. The hardness is defined as the count rate ratio between 8.6–19.7 keV and 6.0–8.6 keV. The start of the light curve is at UT 1997 May 2 18:44; data are at 16 s time resolution. The data points in the HID are 64 s averages. Typical error bars are shown.

of 16 s (129 photon energy channels, effectively covering 2.0–30 keV) and 125 μ s (single-bit mode data in 4 energy channels, effectively covering 2.0–5.0–6.4–8.6–30 keV).

The intensity used in this paper is defined as the 5-PCU count rate in the energy band 2.0–19.7 keV. For the hardness-intensity diagram (HID) we used the 16-s data; the hard color is defined as the count rate ratio between 8.6–19.7 keV and 6.0–8.6 keV. X-ray spectral fits were performed in the range 2–30 keV and a 2% uncertainty was included in the data to account for uncertainties in the PCA response matrix (see e.g. Cui et al. 1997). The X-ray spectra were corrected for background and dead time.

Power density spectra were made from the single-bit mode data, binned to 250 μ s, using 16 s data stretches. In order to study the low-frequency ($\lesssim 100$ Hz) behaviour we fitted the 0.125–128 Hz power spectra with a constant representing the Poisson noise, a Lorentzian and/or a power-law with exponential cut-off to describe peaked noise components, and a power-law describing the underlying continuum (VLFN). To investigate the power spectrum for kHz QPO we fitted the 256–2048 Hz power spectra with a function described by a constant, a Lorentzian to describe QPO, and a broad sinusoid to represent the dead-time modified Poisson noise (Zhang et al. 1995; Zhang 1995). Errors quoted for the power spectral parameters were determined using $\Delta\chi^2=1$. Upper limits were determined using $\Delta\chi^2=2.71$, corresponding to 95% confidence levels.

3. Results

In Figs. 1a and b we show the light curve and the corresponding HID. During the first two contiguous data segments the source was in the NB, while in the last one it was in the FB. Since the flaring in the FB of GX 349+2 is known to have higher amplitudes than seen here (e.g. Ponman et al. 1988), we reckon that the source traced out only the lower part of its FB.

We combined all power spectra of the first two segments (NB) and of the third segment (lower FB). The noise component between ~ 3 –20 Hz in the NB power spectrum (Fig. 2a) can be described by a cut-off power-law ($\chi^2_\nu/\text{degrees of freedom [dof]}$

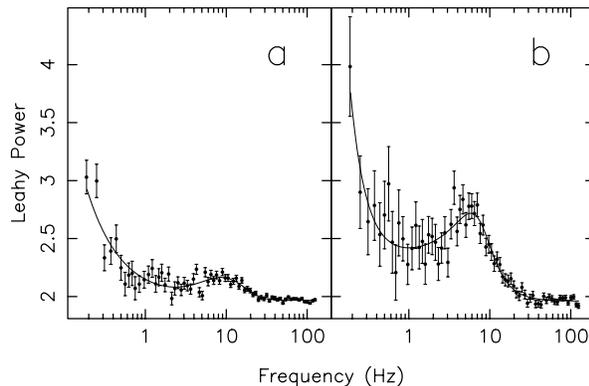


Fig. 2a and b Leahy normalized power spectra (effectively 2.0–30 keV), focussed on the low-frequency ($\lesssim 100$ Hz) range, for the first two continuous (**a**, NB) and the last continuous (**b**, FB) data segments.

of 116/65) with a strength of $1.9 \pm 0.3\%$ (0.1–100 Hz), and power law index and cut-off frequency of -2.4 ± 0.4 and 3.8 ± 0.6 Hz, respectively. A Lorentzian fit to this noise component resulted in a fractional rms, FWHM, and centroid frequency, ν_c , of $2.7 \pm 0.1\%$, 16 ± 2 , and 9.4 ± 0.5 , respectively (χ^2_ν/dof of 111/65). Formally this “peaked noise” component in the NB is no QPO, since $\text{FWHM} > 0.5\nu_c$ (e.g. van der Klis 1995a).

A cut-off power-law fit to the noise component in the FB power spectrum gave a fractional rms (0.1–100 Hz), power-law index and cut-off frequency of $3.1 \pm 0.3\%$, -1.9 ± 0.3 , and 3.6 ± 0.4 Hz, respectively ($\chi^2_\nu/\text{dof} = 70.5/65$). A Lorentzian fit to this noise component resulted in a fractional rms, FWHM, and frequency of $4.2 \pm 0.1\%$, 11.0 ± 0.7 Hz, and 5.8 ± 0.2 Hz, respectively ($\chi^2_\nu/\text{dof} = 67.3/65$). Formally, also this “peaked noise” component may not be regarded as QPO.

In order to study the energy dependence of the fractional rms of the peaked noise in the NB and lower FB, we fitted the power spectra in the four available energy bands. The peaked noise in the NB was modeled with a cut-off power law and that in the FB as a Lorentzian. The power-law index, Γ , and cut-off frequency, $\nu_{\text{cut-off}}$, and the centroid frequency, ν_c , and FWHM were fixed in this process, respectively for the NB and FB peaked noise component. The results are given in Table 1. The strength of the peaked noise component in the FB increases significantly with energy, while that in the NB may do so too, but is consistent with being constant.

We found no narrow QPO on the NB. We derived 95% confidence upper limits on the strength (2.0–30 keV) of such NBO by adding a Lorentzian to the NB power spectrum, fixing the FWHM to a typical value of 3 Hz (see e.g. van der Klis 1995b). This resulted in upper limits between 0.6 and 0.9%, for frequencies between 4 and 9 Hz.

We also searched for the presence of kHz QPO in GX 349+2. No strong kHz QPO can be found in the power spectra. A weak QPO peak near 1020 Hz was discerned in the 2.0–30 keV band power spectrum (Fig. 3), however, perhaps due to the relative shortness of the observation, it was only significant at the 2.6σ level (estimated from an F-test for the inclusion of the QPO and from the 68% confidence error-scan of the integral power in

Table 1. NB and FB peaked noise energy dependence

Effective energy range (keV)	NB peaked noise fractional rms amplitude ¹ (%)	FB peaked noise fractional rms amplitude ² (%)
2.0–5.0	1.6±0.1	3.1±0.1
5.0–6.4	1.6±0.3	4.3±0.2
6.4–8.6	2.1±0.3	5.0±0.3
8.6–30	2.5±0.2	5.6±0.2

¹ Modeled as cut-off power law; Γ and $\nu_{\text{cut-off}}$ fixed, see text.

² Modeled as a Lorentzian; FWHM and ν_c fixed, see text.

the χ^2 -space, i.e. $\Delta\chi^2=1$). When described with a Lorentzian the QPO had a centroid frequency, FWHM, and fractional rms of 1020 ± 11 Hz, 40 ± 25 Hz, and $1.0\pm 0.2\%$, respectively. Since kHz QPO in Z sources are hard (van der Klis et al. 1996a,b, 1997a, Wijnands et al. 1997b, 1998) we determined the rms dependence of the 1020 Hz feature as a function of energy (fixing the centroid frequency and FWHM to the above derived values). This resulted in 95% confidence upper limits of 1.6%, 2.1%, 2.1%, and 1.4%, for the effective energy ranges 2.0–5.0 keV, 5.0–6.4 keV, 6.4–8.6 keV, and 8.6–30 keV, respectively. This provides no additional indications as to the reality of the kHz QPO peak.

In order to compare our results with previous EXOSAT observations, we determined the position of the source during the RXTE observations in the CD and HID of Kuulkers & van der Klis (1995a). We therefore fitted a mean NB X-ray spectrum and folded the fit through the EXOSAT ME response. The resulting mean value for the intensity corresponds to the NB of the EXOSAT HID at the highest overall intensities.

4. Discussion

We found peaked noise (Lorentzian with FWHM ~ 11 Hz and $\nu_c\sim 6$ Hz) when GX 349+2 was in the lower part of the FB with a fractional rms of $\sim 4\%$ (2–30 keV). Its strength increased significantly from $\sim 3\%$ to $\sim 5.5\%$ with increasing photon energy of ~ 3 keV to ~ 10 keV. In the NB we found a weaker and somewhat broader noise component (Lorentzian with rms of $\sim 3\%$ [2–30 keV], FWHM of ~ 16 Hz and ν_c of 9.4 Hz).

Very similar behaviour was reported from extensive EXOSAT observations of GX 349+2 by Ponman et al. (1988). Their peaked noise (referred to as “broad QPO”) was strongest when GX 349+2 was in transition between its quiescent (i.e. NB) and peak (upper FB) intensities. When strongest ($\sim 3.2\%$, 1–10 keV) its FWHM and ν_c were similar to ours (see also Hasinger & van der Klis 1989). It seems therefore likely we have observed the same phenomenon. Our analysis of the RXTE X-ray spectrum in the NB shows that indeed our observation falls in the same part of the HID diagram as the observations by Ponman et al. (1988); see Kuulkers & van der Klis (1995a). The peaked noise observed by Ponman et al. (1988) became broader in the NB (and therefore more consistent with a broad-band noise; see also Hasinger & van der Klis 1989), a similar behaviour as we

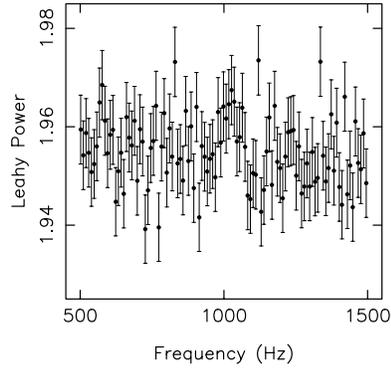


Fig. 3. Leahy normalized power spectrum (effectively 2.0–30 keV) of the whole data set, focussed on the kHz QPO region. A possible QPO peak near 1020 Hz is discernable at the 2.6σ level.

found. Further up the FB the peaked noise became narrower and rapidly weaker (Ponman et al. 1988).

EXOSAT observations taken ~ 1 year before those described by Ponman et al. (1988), however, showed a different behaviour. At that time the power spectrum showed a peak with fractional rms of $\sim 2\%$, and centroid frequency and FWHM of ~ 11 Hz and ~ 7.5 , respectively (Lewin et al. 1985), and it was at lower overall intensities (see Kuulkers & van der Klis 1995a). Observations with the Einstein solid state spectrometer (SSS) also revealed a peak with centroid frequency of ~ 11 Hz and FWHM of ~ 4 Hz (Christian et al. 1988), when the source was flaring (Christian et al. 1988; see also Christian & Swank 1997). Note that this particular peak was narrower than $0.5\nu_c$. The power spectral peaks of Lewin et al. (1985) and Christian et al. (1988) were reported to be significant at the $\sim 3\sigma$ level. We note that folding the “low-state” (i.e. NB) Einstein SSS and monitor proportional counter spectrum of GX 349+2 (Christian & Swank 1997) through the EXOSAT ME response matrix gives intensities which lie in between the mean NB intensities of the two EXOSAT observations in Kuulkers & van der Klis (1995a).

The above described behaviour is in contrast with that found in Sco X-1 (Hertz et al. 1992, Dieters & van der Klis 1998) and GX 17+2 (Penninx et al. 1990). These sources and GX 349+2 show comparable properties in the CD and HIDs (although no HB has been observed for GX 349+2) and similar light curves (e.g. Schulz et al. 1989, Hasinger & van der Klis 1989). However, in both Sco X-1 and GX 17+2 a strong NBO (1–3% rms [2–10 keV], 2–6 Hz FWHM, 5–7 Hz centroid frequency) merges smoothly into FBO (1–3%, ~ 2 –10 keV) when the source moves from the NB to the FB. In the FB the FBO frequency increases from ~ 6 –7 Hz up to ~ 20 Hz and becomes simultaneously broader (up to ~ 20 Hz). On the other hand, we note that the energy (Ponman et al. 1988, this paper) and time lag (Ponman et al. 1988) behaviour of the peaked noise in the FB of GX 349+2 are very similar to that seen in the NBO/FBO in Sco X-1 (Dieters et al., in preparation). In both sources the (broad) QPO increases in strength at higher energies and there is no evidence for a lag between low-energy and hard-energy QPO. Also in GX 17+2 the FBO becomes stronger as a function of energy (Penninx et al. 1990). So, perhaps the peaked noise

seen in GX 349+2 still have a similar origin as the NB/FB QPO in Sco X-1 and GX 17+2.

No narrow NBO like that found in the other 5 Z sources (see e.g. Hasinger & van der Klis 1989) has ever been observed in GX 349+2. We derived upper limits on the presence of typical NBO ($\sim 0.9\%$, 2–30 keV), i.e. below the NBO fractional rms range (1–4%, ~ 2 –10 keV) observed in the other sources. Moreover, as shown above, the power spectral behaviour of GX 349+2 at roughly the same position in the Z track seems to be different at different overall intensities. Changes in the fast timing behaviour in Cyg X-2 at the same position in the CD or HID as a function of overall intensity were recently found by Wijnands et al. (1997a). They reported a decrease in strength of the NBO from medium (2–3%) to high overall intensities ($< 1\%$). Changes in the NBO properties between the different Z sources have been discussed by Kuulkers & van der Klis (1995b). NBO were suspected to be weak or absent when a source is viewed at a relatively high inclination. The absence of a strong NBO in GX 349+2, however, is in contradiction with our earlier suggestion that GX 349+2, Sco X-1 and GX 17+2 are viewed at lower inclinations and Cyg X-2, GX 5–1 and GX 340+0 at higher inclinations (see also the discussion in Kuulkers et al. 1997).

We note that broad power spectral peaks in the lower FB, near the NB/FB vertex, have also been reported for GX 17+2 (FBO, Penninx et al. 1990) and Cyg X-2 (Wijnands et al. 1997a), with $\nu_{\text{peak}} \sim 6$ –7 Hz and FWHM ~ 10 Hz. However, these peaks changed smoothly into typical NBO when the source moved from the lower FB into the NB. Peaked broad-band noise components (LFN) in Z sources have been observed in Sco X-1 and GX 17+2 (Dieters & van der Klis 1998, Penninx et al. 1990, Kuulkers et al. 1997). However, these were observed *only* in the HB and upper NB, with peak frequencies of 2–3 Hz, and were absent in the rest of the NB and in the FB. It is therefore unlikely the observed peaked noise in GX 349+2 is a manifestation of LFN.

The peaked noise in GX 349+2 bears more resemblance in shape to the peaked noise components (referred to as high-frequency noise) seen in atoll sources in their so-called banana state (see Hasinger & van der Klis 1989, van der Klis 1995b, and references therein). For example, the peaked noise in GX 3+1 found by Lewin et al. (1987, see also Hasinger & van der Klis 1989), with centroid frequency, FWHM and fractional rms of ~ 8 Hz, ~ 8 Hz and $\sim 3.5\%$, respectively, is very similar to that found by Ponman et al. (1988) and us. Moreover, the very-low-frequency noise (VLFN) in the bright atoll source GX 13+1 was found to be anomalously strong (Hasinger & van der Klis 1989), and similar to FB VLFN. This shows that some members of the atoll and Z sources exhibit features of both classes and may suggest some overlap between the classes. The recently discovered ~ 60 Hz QPO in GX 13+1 (Homan et al. 1998) may be comparable to HB QPO and is even a stronger suggestion for the existence for such overlap.

So far, kHz QPO has been observed in the four Z sources Sco X-1 (van der Klis et al. 1996a, 1997b), GX 5–1 (van der Klis et al. 1996b), GX 17+2 (van der Klis et al. 1997a, Wijnands et al. 1997b) and Cyg X-2 (Wijnands et al. 1998). We found only

weak evidence of kHz QPO (at 2.6σ confidence level), with a fractional rms, FWHM and centroid frequency of $\sim 1\%$ (2–30 keV), ~ 40 Hz and ~ 1020 Hz, respectively. We note that the expected frequency and fractional rms of the (higher frequency) kHz QPO in Sco X-1, GX 17+2 and Cyg X-2 in the lower NB/FB are > 1000 Hz and $\sim 1\%$, respectively. This is consistent with our observations.

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