THE DISCOVERY OF A STATE-DEPENDENT HARD TAIL IN THE X-RAY SPECTRUM OF THE LUMINOUS Z SOURCE GX 17+2

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ABSTRACT

We report results of a BeppoSAX (0.1–200 keV) observation of the Z-type low-mass X-ray binary GX 17+2. The source was on the so-called horizontal and normal branches. Energy spectra were selected based on the source position in the X-ray hardness-intensity diagram. The continuum could be fairly well described by the sum of a ∼0.6 keV blackbody, contributing ∼10% of the observed 0.1–200 keV flux, and a Comptonized component, resulting from upscattering of ∼1 keV seed photons by an electron cloud with temperature of ∼3 keV and optical depth of ∼10. Iron K line and edge were also present at energies of ∼6.7 and ∼8.5 keV, respectively. In the spectra of the horizontal branch, a hard tail was clearly detected at energies above ∼30 keV. It could be fit by a power law of photon index ∼2.7, contributing ∼8% of the source flux. This component gradually faded as the source moved toward the normal branch, where it was no longer detectable. We discuss the possible origin of this component and the similarities with the spectra of atoll sources and black hole X-ray binaries.

Subject headings: accretion, accretion disks — stars: individual (GX 17+2) — stars: neutron — X-rays: general — X-rays: stars

1. INTRODUCTION

Low-mass X-ray binaries (LMXBs) hosting an old accreting neutron star (NS) display X-ray spectra that are still relatively poorly understood. The modern classification of LMXBs relies on the branching displayed by individual sources in the X-ray color-color diagram (Hasinger & van der Klis 1989) and comprises a Z class (source luminosities close to the Eddington luminosity $L_{\text{edd}}$) and an atoll class (usually luminosities of $\sim 0.01 – 0.1 L_{\text{edd}}$). Considerable evidence has been found that the mass accretion rate of individual Z sources increases from the top left to the bottom right of the Z pattern (e.g., Hasinger et al. 1990), i.e., along the so-called horizontal, normal, and flaring branches (HB, NB, and FB, respectively). While the spectra of atoll sources often extend up to energies of $\geq 100$ keV and present interesting analogies with the hard X-ray component of black hole candidate (BHC) binaries, the X-ray spectra of Z sources are comparatively soft and dominated by thermal-like components with exponential cutoff at energies $\leq 10$ keV. Attempts at decomposing the X-ray spectra of Z sources have employed two (or more) components, the origin of which is still debated (e.g., Mitsuda et al. 1984; White et al. 1986; Psaltis, Lamb, & Miller 1995). A tracking of the spectral variations along the Z pattern was attempted (see, e.g., Hasinger et al. 1990; Hoshi & Mitsuda 1991; Schulz & Wijers 1993; Asai et al. 1994 and references therein); the results were inconclusive, since in different decompositions the spectral variations can be ascribed to different components. Moreover, it is not clear whether any of the proposed components evolve with continuity from Z to atoll sources. The timing properties of LMXBs, on the contrary, possess a clear continuity along the different branches of each source and also a remarkable similarity across Z and atoll sources (e.g., Wijnands & van der Klis 1999; Psaltis, Belloni, & van der Klis 1999).

We report here the results of an extensive study with BeppoSAX of the Z source GX 17+2. The source usually describes a complete Z pattern in the color-color diagram in a relatively short time (3–4 days). The parameters of the noise components as well as the frequency of the quasi-periodic oscillations (QPOs) are well correlated with the position in the color-color diagram (e.g., Langmeier, Hasinger, & Truemper 1990; Kuulkers et al. 1997; Wijnands et al. 1997). The source occasionally shows X-ray bursts that are often long and involve a moderate increase of the X-ray flux (∼50%; Kahn & Grindlay 1984; Tawara et al. 1984); Sztajno et al. (1986) interpret them as type I X-ray bursts. Studies of the source X-ray spectrum were carried out by White, Stella, & Parmar (1988), Langmeier et al. (1990), Schulz & Wijers (1993) based on EXOSAT spectra, and Hoshi & Asaoka (1993) based on Ginga spectra. In all cases, the spectrum was found to steepen rapidly above energies of a few tens of keV.

2. OBSERVATIONS AND ANALYSIS

A pointed observation of GX 17+2 was carried out between 1999 October 4 04:52 UT and October 9 01:10 UT, with the narrow-field instruments (NFIs) on board BeppoSAX (Boella et al. 1997). These consist of four co-aligned instruments covering the 0.1–200 keV energy range: a low-energy concentrator/spectrometer (LECS; 0.1–10 keV), two medium-energy concentrator/spectrometers (MECSs; 1.3–10 keV), a high-pressure gas scintillator proportional counter (HPGSPC; 7–60 keV), and a phoswich detection system (PDS; 13–200 keV). The effective exposure was 56 ks in the LECS, 193 ks in the two MECS, 160 ks in the HPGSPC, and 78 ks in the PDS. In the LECS and MECS images, data were extracted from circular regions centered on GX 17+2, with radii of 8′ and 4′, respectively. Data extracted from the same detector regions during blank field observations were used for background subtraction. Background
subtraction was obtained in the PDS from data accumulated during the off-source intervals and in the HPGSPC by using spectra accumulated from dark Earth data. All the available evidence indicates that there were no significant contaminating sources in the field of view of the HPGSPC and PDS: the off-source PDS count rates are in the expected range; the HPGSPC and PDS spectra align well with each other and with the MECS spectra; finally, evidence for a hard X-ray component in GX 17+2 was found only when the source was in a specific state (see below).

Four bursts occurred during our observation; these were excluded from the subsequent analysis. Figure 1 shows the hardness-intensity diagram (HID), where the hard color (HC) is the ratio of the 7–10.5 to the 4.5–7 keV MECS count rates and the intensity is the 4.5–10.5 keV count rate. The HB and NB are clearly seen. A comparison with a longer RXTE observation, simultaneous to the BeppoSAX observation, shows that the BeppoSAX HID covers the entire HB and NB (J. Homan et al. 2000, in preparation). In order to investigate the source spectrum in different regions of the HID, we accumulated the energy spectra of each NFI over the seven different HC intervals defined by the following boundaries: 0.26, 0.288, 0.3, 0.31, 0.315, 0.32, 0.335, and 0.37. These spectra are labeled A through G in order of decreasing HC. A systematic error of 1% was added to the data of each spectrum. As is customary, in the spectral fitting procedure we allowed for different normalizations in the LECS, HPGSPC, and PDS spectra relative to the MECS spectra, and checked a posteriori that derived values are in the standard range for each instrument.

In line with previous studies (Mitsuda et al. 1984; White et al. 1988), we tried several two-component models to fit the X-ray continuum of GX 17+2. These were a blackbody or a disk multicolor blackbody (DISKBB; Mitsuda et al. 1984) for the soft component together with a blackbody or models of thermal Comptonization, such as a power law with cutoff, COMPST (based on the solution of the Kompaneets equation given by Sunyaev & Titarchuk 1980) or COMPTT (in which relativistic effects are included and the dependence of the scattering opacity on seed photon energy, a free parameter of the model, is taken into account; Titarchuk 1994), for the harder component. In all cases, the addition of an Fe Kα line at ~6.7 keV proved necessary (probability of chance improvement $<10^{-3}$), while an edge at ~8.5 keV improved the fits at ~98%–99% confidence level. The best fit to the continuum of GX 17+2 was obtained using a blackbody plus the COMPST Comptonization model (reduced χ², averaged on the intervals, of $\chi^2_r \sim 1.26$ vs. $\chi^2_r \sim 1.31$–1.51 for the other models). The blackbody had a temperature of $kT_{\text{bb}} \sim 0.6$ keV and contributed ~10% of the observed 0.1–200 keV flux. The blackbody equivalent radius was $R_{\text{bb}} \sim 37$ km (using a distance of 7.5 kpc; Penninx et al. 1988). The temperature of the seed photons for the Comptonized component was $kT_{\text{w}} \sim 1$ keV. Following in’t Zand et al. (1999), we derived the effective Wien radius of the seed photons; this was $R_{w} = 12–17$ km. The temperature and optical depth of the (spherical) Comptonization region were $kT_{\text{c}} \sim 3$ keV and $\tau \sim 10–12$, respectively.

A marked excess of counts above ~30 keV was clearly apparent in the spectrum from the upper HB (spectrum A, HC > 0.335). This excess could not be fit by any of the two-component continuum models that we tried. Therefore, we added an extra component to the model above. With the addition of a power law, the χ² decreased from 339 (for 239 degrees of freedom)[dof] to 254 (237 dof) in the case of spectrum A. An F-test indicates that the probability of chance improvement is negligible ($<10^{-13}$). This additional component was detected up to energies of ~100 keV, had a best-fit photon index $\sim 2.7$, and contributed ~8% of the 0.1–200 keV source flux. Other models (e.g., a thermal bremsstrahlung with $kT \sim 30$ keV) gave comparably good results. The addition of a power-law component, with photon index 2.7, also improved the fit of spectra B, C, and D (from the lower HB, $0.31 < HC < 0.33$). We note that the source went back several times to the same regions of the HB, each time with the same effect on the hard tail. Results from these three-component fits to the BeppoSAX spectra of GX 17+2 are given in Table 1.

On the contrary, the spectra from the NB (spectra E, F, and G) did not show any evidence for a high-energy excess. To study the flux variations of the high-energy component across the HB and NB, we fixed the photon index to 2.7 (i.e., the best-fit value for spectrum A) and derived upper limits on the normalization. It is apparent from Table 1 that the flux in the high-energy power law must have decreased by at least a factor of ~20, from the upper HB (spectrum A) to the lower NB (spectrum G). See also Figure 2, which shows spectra A and G and the residuals with respect to the corresponding best fits.

3. DISCUSSION

Our observation of GX 17+2, the first to extensively study the X-ray spectrum of a Z source with sensitive instrumentation covering a broad energy range, led to the discovery of a high-energy component extending up to ~100 keV, at least. This component was detected in the HB of the source, where it contributed up to ~8% of the 0.1–200 keV source flux. On the contrary, the NB spectra did not show any evidence for a high-energy excess (upper limit of ~0.4% in the lower NB). Our modeling of the X-ray continuum up to energies of ~20–30 keV comprises a blackbody, contributing ~10% of the ~200 keV flux, and a Comptonized spectrum, resulting from the upscattering of seed photons with ~1 keV Wien spectrum. This continuum model might be regarded as a generalization of the...
within the spectral decomposition adopted here, are mainly re-

to a monotonic decrease of the electron temperature and optical 

evolution across the HB to the lower NB can be ascribed mainly 

absorbed cyclotron emission (see Psaltis et al. 1995). The spectral 

photons of the Comptonized spectrum are emitted at X-ray en-

radii are (et al. 1986, 1988). (1) The blackbody has a lower temperature 

ªwesternº model, with several important differences (see White 

et al. 2000 DI SALVO ET AL. L121 


ted here, are mainly re-

ponsible for the decrease of the HC from the HB to the NB. 

On the contrary, the soft part of the spectra remains nearly un-

changed, in agreement with the fact that the HB and NB of GX 

17+2 are almost vertical in the color-color diagram (soft color 

on the x-axis; see Wijnands et al. 1997). A more detailed dis-

ussion of the new continuum model for the X-ray spectrum of 

GX 17+2 in relation to the properties of the X-ray bursts from 

the source will be presented elsewhere. We note that the same 

continuum model has been used to describe the X-ray spectrum 
of atoll sources (e.g., Guainazzi et al. 1998; Barret et al. 2000). 


table 1

| Parameter                  | A            | B            | C            | D            | E            | F            | G            |
|----------------------------|--------------|--------------|--------------|--------------|--------------|--------------|--------------|
| Hard color                 | (0.335–0.37) | (0.32–0.335) | (0.315–0.32) | (0.31–0.315) | (0.3–0.31)   | (0.288–0.3)  | (0.26–0.288) |
| $N_H$ ($\times 10^{22}$ cm$^{-2}$) | 2.2 ± 0.2    | 2.12 ± 0.08  | 1.92 ± 0.07  | 1.97 ± 0.06  | 1.83 ± 0.06  | 1.80 ± 0.05  | 1.85 ± 0.06  |
| $kT_\text{in}$ (keV)        | 0.63 ± 0.06  | 0.52 ± 0.04  | 0.58 ± 0.04  | 0.57 ± 0.04  | 0.54 ± 0.04  | 0.56 ± 0.04  | 0.56 ± 0.04  |
| $R_\text{in}$ (km)         | 35 ± 7       | 47 ± 8       | 38 ± 6       | 40 ± 6       | 43 ± 6       | 41 ± 6       | 41 ± 6       |
| $kT_\text{w}$ (keV)        | 1.07 ± 0.09  | 0.95 ± 0.05  | 1.01 ± 0.05  | 1.01 ± 0.05  | 1.01 ± 0.03  | 1.03 ± 0.04  | 1.03 ± 0.04  |
| $kT_e$ (keV)               | 3.28 ± 0.06  | 3.21 ± 0.05  | 3.25 ± 0.05  | 3.15 ± 0.04  | 3.08 ± 0.04  | 3.13 ± 0.04  | 3.04 ± 0.04  |
| $\tau$                     | 11.6 ± 0.4   | 11.0 ± 0.3   | 10.6 ± 0.2   | 10.6 ± 0.2   | 9.8 ± 0.2    | 9.9 ± 0.2    | 9.5 ± 0.2    |
| $R_\text{w}$ (km)          | 12 ± 2       | 17 ± 2       | 15 ± 1       | 15 ± 1       | 16 ± 1       | 15 ± 1       | 15 ± 1       |
| Photon index               | 2.7 ± 0.2    | 2.7 (fixed)  | 2.7 (fixed)  | 2.7 (fixed)  | 2.7 (fixed)  | 2.7 (fixed)  | 2.7 (fixed)  |
| Power-law $N_\text{e}$     | 1.3 ± 0.7    | 0.6 ± 0.2    | 0.4 ± 0.2    | 0.4 ± 0.1    | <0.27        | <0.25        | <4.3 × 10$^{-2}$ |
| $E_{\text{in}}$ (keV)      | 6.74 ± 0.09  | 6.78 ± 0.09  | 6.7 ± 0.1    | 6.7 ± 0.1    | 6.7 ± 0.1    | 6.7 ± 0.1    | 6.74 ± 0.08  |
| FWHM (keV)                 | 0.6 ± 0.3    | 0.4 ± 0.3    | 0.5 ± 0.3    | 0.5 ± 0.3    | 0.5 ± 0.4    | 0.5 ± 0.3    | 0.5 ± 0.4    |
| $I_\text{e}$ ($\times 10^{-3}$ photons cm$^{-2}$ s$^{-1}$) | 6 ± 2 | 5 ± 1 | 5 ± 1 | 4 ± 1 | 4 ± 1 | 4 ± 1 | 5 ± 1 |
| $F_{\text{line}}$ (keV)   | 8.7 ± 0.3    | 8.8 ± 0.3    | 8.5 ± 0.3    | 8.6 ± 0.3    | 8.6 ± 0.3    | 8.5 ± 0.3    | 8.5 ± 0.2    |
| FWHM (keV)                 | 3 ± 1       | 3 ± 1        | 3 ± 1        | 3 ± 1        | 2 ± 1        | 2 ± 1        | 5 ± 1        |
| $r_{\text{fwhm}}$ ($\times 10^{-3}$) | 1.84 | 1.82 | 1.81 | 1.81 | 1.81 | 1.69 | 1.71 | 1.52 |
| X$_{\text{abs}}$ (dof)     | 1.07 (237)  | 1.21 (238)  | 1.04 (237)  | 1.11 (237)  | 1.27 (236)  | 1.26 (237)  | 1.22 (236)  |
| $F$-test                    | $1.2 \times 10^{-11}$ | $1.1 \times 10^{-10}$ | $4.9 \times 10^{-12}$ | $2.1 \times 10^{-14}$ | 0.14 | 0.30 | 0.98 |

Note.—The model consists of a blackbody, COMP, a power law, a Gaussian emission line, and an absorption edge. For each spectrum the corresponding range of HC is indicated. Uncertainties are at the 90% confidence level for a single parameter. The power-law normalization is in units of photons keV$^{-1}$ cm$^{-2}$ s$^{-1}$ at 1 keV. The total flux is in the 0.1–200 keV energy range. $F$-test is the probability of chance improvement when the power law is included in the spectral model.

Fig. 2.—Spectra A (upper HB, left panels) and G (lower NB, right panels) and the corresponding best-fit models (upper panels) and residuals in units of $\sigma$ (lower panels).
The detection of an absorption edge at \(\sim 8.5\) keV is new. The energy of the line and absorption edge indicate a high-ionization stage of Fe (Fe xxiii–xxv).

The main result of our study is the discovery of a hard component in the X-ray spectrum of GX 17+2. This component was detected only in the HB, dominating the spectrum between \(\sim 40\) and \(\sim 100\) keV. A Gamma = 2.7 power-law model provided an adequate fit. This is the first time that a hard X-ray component is detected in the HB of a Z source. Previously, a power-law–like hard excess was detected in the Ginga data of GX 5–1 (Asai et al. 1994). GX 5–1 was in the NB and FB during the Ginga observation, and the intensity of the power-law component decreased from the NB to the FB. A hard X-ray component was also detected in the BeppoSAX data of Cyg X-2, but the source state was not reported (Frontiera et al. 1998). These results indicate that hard components are probably a common feature of Z sources and that their intensity decreases from the HB to the NB and the FB, i.e., for increasing mass accretion rates. We note that this behavior is similar to that observed in LMXBs of the atoll group and BHCs, where the relative importance of the hard X-ray component is often highest in the low-luminosity source states (the island state of atoll source and the low and intermediate states of BHCs; see, e.g., Nowak 1995; Barret et al. 2000).

Theoretical interpretations for this effect have already been discussed; for example, at high accretion rates the corona might be efficiently cooled by increased Comptonization losses or swept away by radiation pressure (Popham & Sunyaev 2000).

Di Matteo & Psaltis (1999) found an interesting correlation between the QPO frequency and the slope of the power-law energy spectra in BHCs (see also Kaaret et al. 1998 for a similar correlation in atoll sources). If the QPO frequency is related to the size of the innermost (optically thick, geometrically thin) disk region, which changes in response to accretion rate variations (as indeed envisaged in a number of QPO models; see van der Klis 2000 for a review), then this correlation might simply reflect variations of the Comptonization parameter in response to variations of the innermost disk radius. We note that, owing to poor statistics, the BeppoSAX GX 17+2 data presented here do not provide independent evidence that the hard component steepens as the source moves from the upper HB and to the NB, i.e., the path along which the QPO frequency increases. Yet the data are consistent with this behavior. We note that there might exist a relationship between the presence of the hard X-ray component and QPOs. This is suggested by the facts that (1) the hard X-ray component of GX 17+2 is most pronounced over the source state(s) in which both the kilohertz and HB QPOs are detected and reach the highest rms amplitudes and (2) both these rms amplitudes and the contribution from the hard X-ray component to the total spectrum increase dramatically with energy (Wijnands et al. 1997).

The spectrum of GX 17+2 in the HB is similar to the spectra of BHCs in some soft states (intermediate or very high states). These are dominated by soft emission with characteristic temperatures of \(\sim 1–2\) keV and display a hard power-law component of photon index \(\sim 2–3\), extending to several hundred keV and contributing a few percent of the total luminosity (see, e.g., Grove et al. 1998). At a purely phenomenological level, the presence of a similar high-energy tail in an otherwise soft NS system indicates that this tail should not be considered a signature of BHC accretion. The origin of this extended power-law tail in some soft states of BHCs is still debated. A model that might explain the hard power-law component in the soft state of both NS and BHC systems is the hybrid thermal/nonthermal corona (see, e.g., Gierliński et al. 1999), where a fraction of the energy can be injected in form of electrons with a nonthermal velocity distribution. On the other hand the bulk motion Comptonization model (Ebisawa, Titarchuk, & Chakrabarti 1996) is unlikely to work in luminous NS systems where radial bulk motion would be slowed down by the radiation emitted close to the NS surface.

An alternative possibility is that the hard X-ray component in GX 17+2 originates from the scattering of nonthermal electrons of a jet, which is probably present in the source at low accretion rates. In fact, GX 17+2 is associated with a variable radio source, the flux of which decreases from the HB to the FB (Penninx et al. 1988). This is a general characteristic of Z sources but not of atoll sources (Hjellming & Han 1995; Fender & Hendry 2000 and references therein).

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