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A low/hard state outburst of XTE J1550-564

T. Belloni[1], A. P. Colombo[1,2], J. Homan[1], S. Campana[1], and M. van der Klis[3]

[1] INAF – Osservatorio Astronomico di Brera, Via E. Bianchi 46, 23807 Merate (LC), Italy
e-mail: colombo@merate.mi.astro.it; homan@merate.mi.astro.it; campana@merate.mi.astro.it
[2] Dipartimento di Scienze, Università dell'Insubria, Via Valleggio 11, 22100 Como, Italy
[3] Astronomical Institute "A. Pannekoek" and Center for High-Energy Astrophysics, University of Amsterdam, Kruislaan 403, 1098 SJ Amsterdam, The Netherlands
e-mail: michiel@astro.uva.nl

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Abstract. We present the results of the analysis of 11 RXTE/PCA observations of the January 2002 outburst of the black-hole transient XTE J1550-564. The outburst was rather short, with an e-folding time of ~11 days in the PCA band 3–25 keV. The source was seen in an extreme low/hard state. The energy spectra could be fitted with a power law slightly steepening ($\Gamma \sim 1.4$ to ~1.5) in time, with a high-energy cutoff decreasing from ~300 keV to ~100 keV and some additional features between 6 and 7 keV, while the 3–150 keV flux decreased by a factor of 17. The power spectra were fitted with two broad Lorentzian components, whose characteristic frequencies decreased with the source flux, and whose fractional rms contribution was rather constant. The timing parameters derived can be identified with those observed in other systems. These results show that, although during previous, more luminous, outbursts, a very complex behavior was observed, at low luminosities XTE J1550-564 behaves in a way comparable to most Black-Hole Candidates.

Key words. accretion: accretion disks – stars: binaries – X-rays: stars

1. Introduction

The phenomenology of the X-ray emission from Black Hole Candidates (BHC) is known to be rather complex, especially that of transient systems. Despite the classification into spectral/timing states that emerged in the last decade (van der Klis 1995; Tanaka & Lewin 1995; Belloni 2001), recent observations have revealed a pattern underlying transitions between states more complex than previously realized (see e.g. Belloni 1998, 2001; Homan et al. 2001; Wijnands & Miller 2002; Campana et al. 2002). The large database of observations accumulated with the Rossi X-ray Timing Explorer (RXTE) greatly contributed to this complexity. In particular, in the timing domain, complex features are present in the Power Density Spectra (PDS) of these systems, both narrow and broad (see Belloni et al. 2002 and references therein).

The black hole candidate XTE J1550-564 was discovered as a bright X-ray transient with the All-Sky Monitor (ASM) on board RXTE in September 1998 (Smith 1998). Shortly after that the optical and radio counterparts were discovered (Orosz et al. 1998; Campbell-Wilson et al. 1998); a superluminal ejection has been observed in the radio (Hannikainen et al. 2001).

Send offprint requests to: T. Belloni,
e-mail: belloni@merate.mi.astro.it

The mass of the compact object in this binary system is estimated to be ~10 $M_{\odot}$ (Orosz et al. 2002). Its distance has been assumed to be 6 kpc (Sobczak et al. 1999), although there is quite some uncertainty over this value (see e.g. Orosz et al. 2002). To date the source was observed to be in outburst four times: one major and complex outburst in 1998-99, one in 2000, a small dim outburst in 2001, and a recent outburst in 2002, also rather dim and hard (Swank et al. 2002). Low-level activity between the two latest outburst has also been reported (Swank et al. 2002).

The first outburst was the strongest: in September 1998 the source showed a flare that reached 6.8 Crab in the 2–10 keV band. During this outburst, XTE J1550-564 went through all the canonical BHC states. A complete spectral analysis of these data can be found in Sobczak et al. (2000a), where the data are fitted with the "standard" model for BHC, consisting of the superposition of a disk-blackbody (the soft component) and a power law (the hard component). Homan et al. (2001), studying the second part of the outburst in terms of color-color diagrams, conclude that to describe the behavior of XTE J1550-564, a second parameter besides the mass accretion rate is necessary. The timing behavior of this outburst was very complex (Cui et al. 1999; Remillard et al. 1999; Homan et al. 2001). Radio observations showed that the radio outburst lagged the X-ray outburst by 1.8 days and reached 375 mJy at

843 MHz (Hannikainen et al. 2001). An outflow was observed, with an apparent separation velocity >2c. Optical observations are reported by Jain et al. (2001a): the correlation between optical and X ray flux levels is poor, even showing intervals of anti-correlation.

The 2000 outburst reached a peak flux of ~1 Crab (1.5–12 keV): it also showed state transitions and a timing behavior similar to that of the previous outburst (Tomsick et al. 2001a; Miller et al. 2001; Kalemci et al. 2001; J. Miller, priv. comm.). Radio observations were reported by Corbel et al. (2001): in the VHS/IS intervals the radio emission is quenched, while in the Low State (LS) at the end of the outburst the radio spectrum is inverted. Optical and infrared observations showed that the outburst in the *V* and *H* bands precedes the X-ray outburst by 9–10 days (Jain et al. 2001b).

Finally, the 2001 outburst showed a 2.5–20 keV source flux of ~40 mCrab (measured by RXTE), much weaker than the previous ones. Spectral and timing properties indicate that the source was in the Low/Hard State; energy spectra are described by a power law with a photon index of 1.52 and a neutral iron line. The rms level of timing noise is about 40% rms (0.01–100 Hz; 2–60 keV; Tomsick et al. 2001b).

As mentioned, in January 2002 the source became active again, after a long period of low-level activity (Swank et al. 2002) and it was observed roughly every two days with RXTE. Radio observations were reported by Corbel et al. (2002), who reported a flat radio spectrum, consistent with a LS. As the source was reported to be in the low/hard state, and since the behavior of BHC at low luminosity is usually very similar between different sources (see e.g. Belloni et al. 2002), the analysis of these observations can provide the required link between this source and other systems.

2. Data analysis

We analyzed a set of 11 public TOO observations of XTE J1550-564 made with the RossiXTE satellite (Bradt et al. 1993) in January 2002. The log of the observations is shown in Table 1. RXTE observed the source a few more times after the last observation presented here, but the source had become very weak at those times and we decided to stop our analysis here. We analyzed the data from the Proportional Counter Array (PCA; Jahoda et al. 1996) instrument and from the High Energy X-ray Timing Experiment (HEXTE: Rothschild et al. 1998). For each observation we produced a power density spectrum, X-ray colors and an energy spectrum, following the procedures outlined below.

2.1. All-sky monitor

The All-Sky Monitor (Levine et al. 1996) on board RXTE reaches a sensitivity of ~5–10 mCrab (1.3–12 keV) over one day. Figure 1 shows the light curve of XTE J1550–564 across the 2002 outburst[1], with a bin size of one day. The outburst likely started during Dec. 2001, but the closeness of the Sun made monitoring of the source difficult due to scattered solar X–rays. The situation improved in Jan. 2002, when a clear decrease in the source flux was observed testifying to the latest stages of an outburst. A linear or exponential decay can fit the data equally well, with a count rate decrease of 0.3 per day or an e-folding time of ~15 d.

Table 1. Observation log. PCA rates are renormalized to one PCU. For the definition of X-ray colors, see text.

Obs.	Date (2002)	St. Time (UT)	Exp. (s)	PCA Rate c/s	HR_1	HR_2
A	Jan. 10	21:19	4096	202.4	1.27	0.15
B	Jan. 13	02:34	3584	175.2	1.28	0.15
C	Jan. 15	02:07	4096	145.7	1.28	0.15
D	Jan. 17	09:16	2048	118.2	1.27	0.15
E	Jan. 19	10:50	2560	96.1	1.28	0.15
F	Jan. 21	18:18	2048	77.5	1.30	0.15
G	Jan. 23	05:16	4096	59.2	1.27	0.14
H	Jan. 25	20:53	2048	48.8	1.29	0.14
I	Jan. 26	23:38	2048	41.6	1.30	0.14
J	Jan. 28	20:03	2560	32.7	1.27	0.13
K	Jan. 31	19:14	3072	22.0	1.17	0.11

2.2. PCA/HEXTE: Spectral analysis

To assure that the PCA energy spectra for each individual observation would not contain data from different count rate levels and to identify possible problems with individual PCUs, we produced PCA light curves with a 1-s time resolution using `Standard1` data. All light curves appear to be rather stable in average count rate, with the clear presence of strong noise in the form of rapid flaring. The total count rates of the 11 observations are shown in Table 1, together with two X-ray colors defined as $HR1$ = B/A $HR2$ = C/A, where A, B and C are the net counts in the channel ranges 0–14 (2.0–6.1 keV), 15–37 (6.1–15.8 keV) and 38–46 (15.8–19.4 keV) respectively. The count rates and colors were extracted from the `Standard2` data, after estimation of the background (see below). These bands are the same used by Homan et al. (2001). The total PCA light curve is shown in Fig. 2: an exponential fit gives an e-folding time of 10.6 ± 0.8 days, a figure lower than that estimated from the ASM light curve, possibly due to the difference in energy range. Both X-ray colors appear to be very stable throughout the observing period, despite the count rate decrease by a factor of ten (in the 3.0–25.0 keV band), indicating that the overall spectral shape does not vary much. However, the last spectra tend to be slightly softer. This is confirmed by the results of the spectral fits.

We extracted PCA energy spectra from `Standard2` data, which have an intrinsic time resolution of 16 s. We accumulated a single energy spectrum for each observation, selecting all available PCUs with the exception of PCU0, to avoid problems due to the loss of the propane layer in that unit. The spectra were extracted using standard procedures with FTOOLS V5.1.

[1] `http://xte.mit.edu/lcextrct/`

Table 2. Best-fit spectral and timing parameters for the observations analyzed here. Columns are: observation ID; spectral parameters: power-law photon index, cutoff energy E_c in keV, 3–150 keV unabsorbed flux in 10^{-9} erg cm^{-2} s^{-1}, reduced χ^2; timing parameters: centroid frequency and $HWHM$ of the first Lorentzian, centroid frequency and $HWHM$ of the second Lorentzian, reduced χ^2 with number of degrees of freedom, total integrated fractional rms (0.002–10.0 Hz). All errors and upper limits are at 90% confidence.

Obs.	Γ	E_c (keV)	Flux	χ^2_r (44 d.o.f.)	ν_1^c (Hz)	Δ_1 (Hz)	ν_2^c (Hz)	Δ_2 (Hz)	χ^2_r (d.o.f.)	%rms
A	1.39 ± 0.01	339 ± 52	12.15	0.88	0.016 ± 0.006	0.087 ± 0.011	<0.024	2.132 ± 0.075	0.99 (181)	37
B	1.42 ± 0.01	>566	10.56	1.29	0.012 ± 0.008	0.088 ± 0.010	<0.023	1.957 ± 0.075	1.09 (181)	36
C	1.41 ± 0.01	>411	8.65	1.33	0.016 ± 0.008	0.080 ± 0.010	<0.022	1.863 ± 0.074	1.18 (181)	35
D	1.42 ± 0.02	>474	6.60	1.23	<0.020	0.075 ± 0.015	<0.047	1.655 ± 0.131	0.96 (181)	35
E	1.39 ± 0.02	289^{+139}_{-78}	5.64	0.70	<0.015	0.062 ± 0.012	<0.026	1.579 ± 0.099	0.82 (181)	36
F	1.41 ± 0.02	194^{+75}_{-50}	3.80	1.19	<0.011	0.048 ± 0.009	<0.042	1.448 ± 0.108	0.94 (181)	34
G	1.43 ± 0.02	354^{+200}_{-126}	3.61	0.77	<0.006	0.048 ± 0.005	<0.015	1.472 ± 0.076	1.22 (181)	36
H	1.50 ± 0.02	>178	2.21	1.21	<0.030	0.064 ± 0.025	<0.030	1.318 ± 0.209	1.05 (181)	35
I	1.45 ± 0.03	147^{+114}_{-44}	1.81	1.05	<0.019	0.026 ± 0.008	<0.030	0.992 ± 0.111	1.16 (145)	35
J	1.49 ± 0.03	129^{+229}_{-51}	1.29	1.15	<0.011	0.027 ± 0.009	<0.044	0.907 ± 0.113	1.03 (145)	36
K	1.49 ± 0.05	64^{+50}_{-19}	0.710	1.37	<0.014	0.020 ± 0.006	<0.025	0.630 ± 0.073	1.14 (145)	35

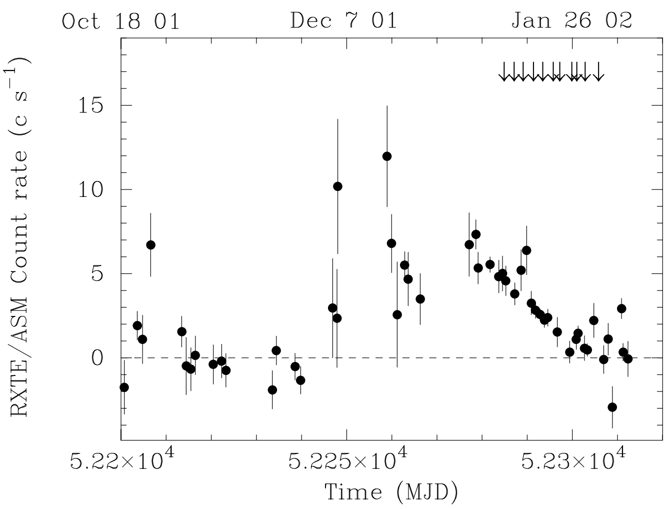

Fig. 1. RXTE/ASM light curve of the 2002 outburst of XTE J1550-564. Each point represents the average of the scans within one day. The times of the pointed observations analyzed here are shown as vertical arrows.

The background was estimated using pcabackest V2.1e and subtracted from the data. PCA response matrices were produced with pcarsp V7.11. For all spectra, only channels 4–52, corresponding to 3–25 keV were used. We extracted HEXTE energy spectra from both instrument clusters using standard FTOOLS V5.1 procedures. For the fits, we considered only channels 10–50, corresponding to 18–150 keV. For the fits, a systematic error of 0.75% was added to each channel. We fitted the energy spectra in the range 3–150 keV with a model consisting of a power law with a high-energy cutoff, a smeared edge and a gaussian emission line. The interstellar absorption was fixed at 8.5×10^{21} cm^{-2} (Tomsick et al. 2001a). For HEXTE, we used only cluster B, besides for observation C for which the cluster B background count rate was abnormally high and prevented the production of a meaningful net spectrum. Results using cluster A are compatible with those reported here. Note that our lower boundary of 3 keV would make it difficult to detect the presence of a very soft component. For observations A through G the Gaussian line was not required by the fit, while for observations H through K the edge was not needed. As the energy of line and edge proved to be very stable through all observations where they were required, they were fixed to 6.4 keV and 7.0 keV respectively. Note that these features can be partly the result of and/or be influenced by instrumental effects. The best fit values for the power-law photon index Γ, the cutoff energy E_c, and the integrated flux, plus the reduced χ^2, are shown in Table 2. Some of the fits are formally unacceptable. Inspection of the residuals shows that the problems are mostly due to a rather large scatter of the HEXTE points, with the exception of observation K, for which a large-scale modulation in the residuals indicate that a more complex model is probably needed. As one can see from Table 2, there is some evidence of a steepening of the power-law index (from ~1.4 to ~1.5) and of a decrease in cutoff energy (from ~300 keV to ~100 keV) while the observed 3–150 keV flux decreases by more than one order of magnitude.

2.3. PCA: Timing analysis

The PCA light curves show strong aperiodic variability, characteristic of the low/hard state. For each observation, we produced a Power Density Spectrum (PDS) in the following way. Individual Leahy-normalized (Leahy et al. 1983) PDS were produced from 512-second stretches of data with a time resolution of 512 s^{-1}, selecting PCA channels 0–35, corresponding to roughly 2–15 keV. The analysis of data above 15 keV did not show significant differences, both in frequencies and rms amplitudes. These PDS were averaged together and the contribution from the Poissonian statistics was subtracted (Zhang et al. 1995). Then the average PDS was normalized to squared fractional rms (Belloni & Hasinger 1990a). Since the signal

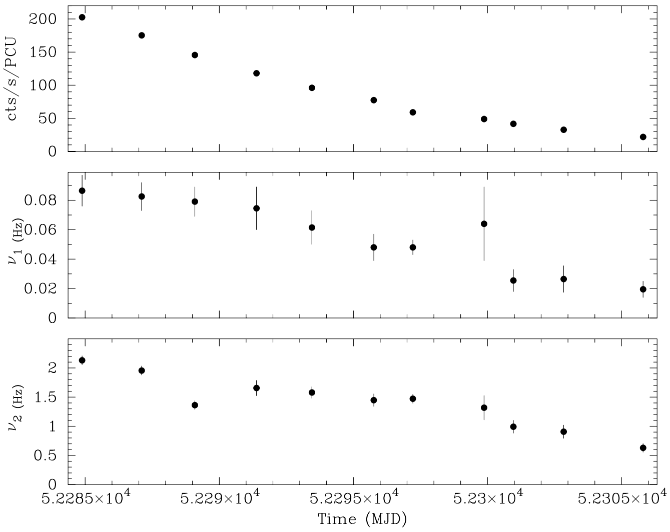

Fig. 2. Top panel: overall PCA light curve (3.0–25 keV) corresponding to the observations analyzed here. Middle and low panel: timing evolution of the characteristic frequencies of the two timing components in the PDS of the source.

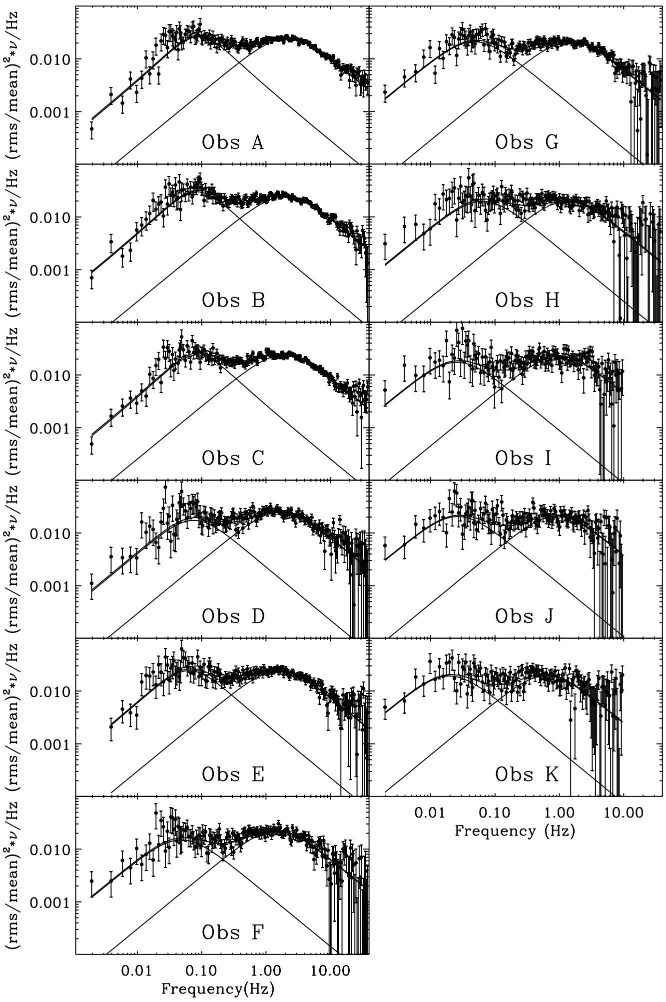

Fig. 3. Power Density Spectra for all the observations presented here in νP_ν form. The best fit models are also shown.

rapidly vanishes at high frequency, we excluded from the analysis bins above 40 Hz for observations A-H, and above 10 Hz for observations I-K. The resulting PDS can be seen in Fig. 3, plotted in a νP_ν representation.

Each PDS was then fitted with a model consisting of Lorentzian components (see Belloni et al. 2002). Fits were performed with XSPEC V.11.1.0. For all power spectra, two Lorentzians were sufficient to achieve an acceptable fit. The best fits are shown in Fig. 3, and the best fit frequency parameters (centroid frequencies $\nu^c_{1,2}$ and $HWHM$ $\Delta_{1,2}$) are reported in Table 1, together with the corresponding reduced χ^2. The best fit is almost always reached for two zero-centered Lorentzians: nevertheless we did not want to force the centroid frequency of the Lorentzians to zero (see Belloni et al. 2002). From Fig. 2, it is evident that as the outburst proceeds and the source count rate decreases, the peak of both Lorentzians in νP_ν moves to lower frequencies. In order to quantify this, we computed the characteristic frequencies $\nu_{1,2}$ of the peaks in νP_ν according to Belloni et al. (2002) and plotted the values as a function of time during the outburst (see Fig. 2). Notice from Table 2 that the total fractional rms integrated in the 0.002–10.0 Hz is remarkably constant, as it is also apparent from the evolution of the power spectra in Fig. 3. Our fits show that also the rms of the single Lorentzian components remains constant throughout the observed part of the outburst.

3. Discussion

The first and major outburst of XTE J1550-564 in 1998-1999 has provided important information about the connection between spectral/timing states in black-hole transients indicating that a second parameter besides the mass accretion rate is governing state transitions (Homan et al. 2001). This outburst has shown all major source states, in addition to an extremely complex phenomenology in the aperiodic time variability, including strong 1–10 Hz QPO peaks with multiple harmonics and high-frequency QPOs between 100 and 280 Hz (Remillard et al. 1999; Homan et al. 2001). The following outburst in 2000 also showed some state transitions (Tomsick et al. 2001a; Kalemci et al. 2001; Miller et al. 2001). At the end of both outbursts, however, the source entered a low/hard state, where the energy spectrum is dominated by the hard power-law component and the power density spectrum shows a strong band-limited noise component. During the short weak outburst of 2001, a PCA observation showed a low/hard state, with a hard energy spectrum (power law with $\Gamma = 1.52$) and a strong (40% fractional rms) band-limited noise (Tomsick et al. 2001b). Violent flaring activity was also reported.

The outburst analyzed here is quite different from the first two and similar to the 2001 one. Throughout all the observations the source was clearly in the low/hard state, both from the spectral and timing analysis. The unabsorbed 3–150 keV flux decreased from 1.2×10^{-8} erg cm^{-2} s^{-1} to 7.1×10^{-10} erg cm^{-2} s^{-1}. At a distance of 6 kpc (Sobczak et al. 1999) these correspond to 5.0–0.2 $\times 10^{37}$ erg s^{-1}. For comparison with Tomsick et al. (2001a), the corresponding 3–25 keV absorbed fluxes are 2.5×10^{-9} erg cm^{-2} s^{-1} and 3.5×10^{-10} erg cm^{-2} s^{-1}. The PCA LS observations from 2000 covered roughly the same range (Tomsick et al. 2001a), and the observation of the 2001 outburst saw the source at a flux intermediate between these limits (Tomsick et al. 2001b). Both the timing (characteristic frequencies) and spectral parameters indicate that indeed we are observing a rather low-flux hard state, where the energy spectrum is very hard and the variability is shifted to low frequencies. Notice that our power-law component is flatter than observed during the whole 2000 outburst, even at similarly low flux levels. As the source flux (and count rate) decreases, we see the low-energy part of the spectrum steepen slightly, and the cutoff moves to lower energies. With the caveat of rather large error bars, a large change in cutoff energy seems to be observed: in the framework of a Comptonization model, this would imply that, in addition to the electron temperature (measured through the observed cutoff), also the optical depth of the Comptonizing cloud increased. Moreover, although we do see a relation between the characteristic frequencies and spectral properties, they seem to be less strong than those observed at higher luminosities (see also below). Notice that we are probably not covering the whole outburst (see Fig. 1), and we cannot exclude the presence of different source states before our observations took place. Indeed, Tomsick et al. (2001a) report that in the 2000 outburst the transition to the LS took place at a slightly higher 3–25 keV luminosity that what we observe in our first pointing.

The PDS can all be fitted with a very simple model consisting of only two Lorentzian components, mostly with zero centroid frequency. This is consistent with recent applications of the Lorentzian models to BHC in the hard state (Belloni et al. 2002; Pottschmidt et al. 2002). However, since only two components are formally needed here, the question arises of the identification of these components in the scheme described by Belloni et al. (2002). As van Straaten et al. (2002) pointed out, this is only possible by comparing a number of observations. Indeed, we can interpret our low-frequency component as L_b and our high-frequency component as L_ℓ (see Belloni et al. 2002). Figure 4 shows our ν_1 and ν_2 values in a ν_ℓ vs. ν_b plot like the one in van Straaten et al. (2002). The points for GX 339-4 from Nowak et al. (2002) and those for XTE J1118+480 from Belloni et al. (2002) are also plotted. Our points agree rather well with those from XTE J1118+480 and with an extrapolation of the highest GX 339-4, but are a factor of two below the the lowest GX 339-4 points. Identifying the low-frequency component with L_b allows us to check the expected correlation between flat-top level (defined here as the value of the L_1 component PDS at our lower frequency boundary of 0.002 Hz) and ν_b (Belloni & Hasinger 1990b; Belloni et al. 2002). Figure 5, where the points from Belloni et al. (2002) are also plotted, shows that the expected correlation is followed with the right −1 slope.

Vignarca et al. (2002) find that in a number of BHC there is a correlation between power-law slope Γ and frequency of the low-frequency QPO. For XTE J1550-564, for QPO frequencies below 2 Hz this correlation is positive and flattens at low QPO frequencies (see also Sobczak et al. 2000b). This means that at low flux, when Γ is as low as 1.5, one expects that large variations in the QPO frequency correspond to small corresponding variations in Γ. Our values correspond to a low-

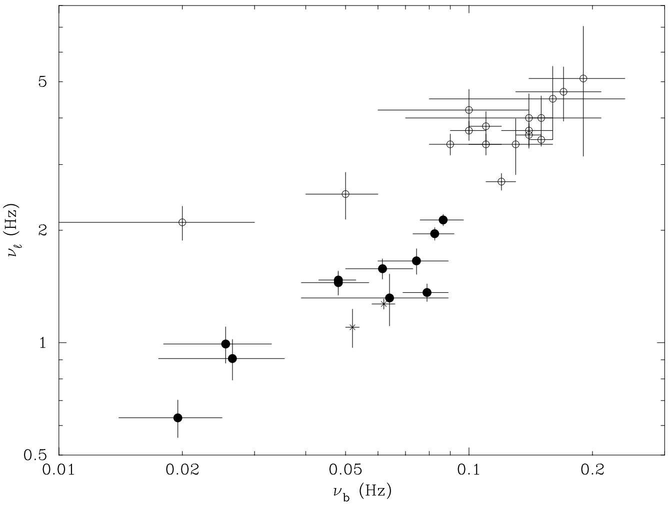

Fig. 4. Correlation between the characteristic frequencies of the two Lorentzian components fitted to the PDS of XTE J1550-564 (filled circles). For comparison, the ν_b and ν_ℓ frequencies for XTE J1118+480 (crosses: Belloni et al. 2002) and GX 339-4 (open circles: Nowak et al. 2002) are shown.

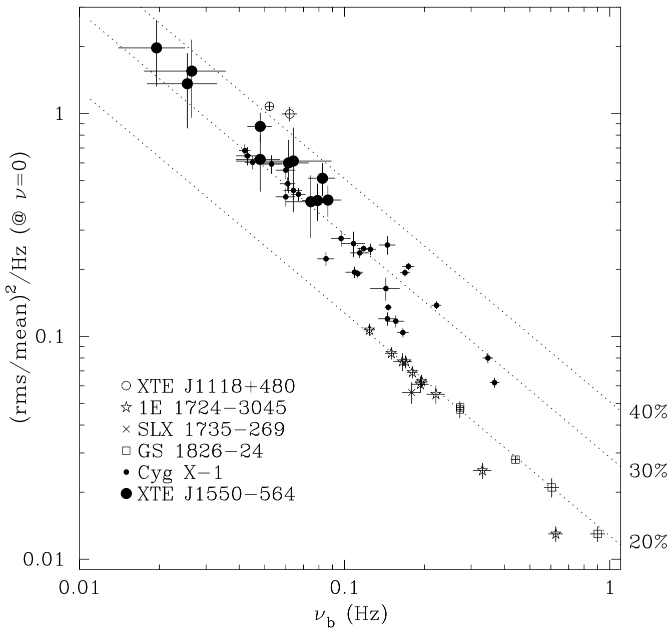

Fig. 5. Correlation between ν_b and flat-top level (see text). The XTE J1550-564 points are marked with large filled circles. All other symbols are the same as Fig. 10 of Belloni et al. (2002). The dotted lines represent constant total fractional rms. Numbers on the y axis are squared rms times two (see Belloni et al. 2002).

frequency extension of the points from Sobczak et al. (2000b); however, they show a weak anticorrelation, opposite to what we expected.

In conclusion, during its short outburst in January 2002, XTE J1550-564 showed spectral and timing features typical of an extreme low/hard state, at least in the PCA/HEXTE observed part of the outburst. Its characteristic parameters in the timing and spectral domains are compatible with those of many other BHC. This indicates that this source, at least at low flux values (and possibly also low values of the mass accretion rate) behaves in the expected way, although the weak spectral variations we observe are not in the direction of what is usually seen from these systems (see also Tomsick et al. 2001a). This allows to link the properties of this source with those of other systems and indicates that bright BHCs while at low luminosities behave in a rather coherent way.

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