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A look with *BeppoSAX* at the low-luminosity Galactic X-ray source 4U 2206+54

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Abstract. A pointed observation of the low-luminosity galactic source 4U 2206+54 was carried out in November 1998 with *BeppoSAX*. The light curve of 4U 2206+54 shows erratic variability on a timescale of ~1 h; neither hardness variations nor time periodicities are detected throughout this 67 ks long observation. Thanks to the wide spectral coverage capabilities of *BeppoSAX* we could observe the source X-ray continuum over three energy decades, from 0.6 to 60 keV. The spectrum could be equally well fitted either with a blackbody plus Comptonization or with a high energy cutoff power law. No iron emission around 6.5 keV was detected, while a tentative detection of a cyclotron resonant feature in absorption is presented. Comparison of the present *BeppoSAX* data with the information available in the literature for this source suggests that 4U 2206+54 is a close binary system in which a (possibly magnetized) NS is accreting from the companion star wind.

Key words. stars: binaries: close – X-rays: binaries – stars: neutron – stars: individuals: 4U 2206+54 – accretion, accretion disks

1. Introduction

Massive X-ray Binaries (MXRBs) are double systems composed of a compact object, generally a neutron star (NS), orbiting an early-type star and accreting matter from it. In X-rays, MXRBs can be seen as persistently bright, with luminosities greater than 10^{35} erg s^{-1}, or present a transient behaviour characterized by quiescent phases, with emissions around 10^{34} erg s^{-1} or less, followed by intense (up to $\sim10^{38}$ erg s^{-1} at peak) outbursts; in several cases, these outbursts show a periodic trend as a result of the orbital motion of the NS along a highly eccentric orbit (see White et al. 1995; van Paradijs 1995 for a review). Usually, the former group is associated with compact objects steadily accreting from the companion via Roche lobe overflow and/or stellar wind, while in the latter one accretion is discontinuous and occurs when the compact source enters a disk-like envelope around the companion star or, more generally, interacts more closely with the companion as it approaches periastron (e.g., Corbet 1986).

There are however MXRBs which do not fit this classification, i.e. the so-called low-luminosity MXRBs, characterized by their relatively low persistent emission in the X-ray domain (10^{34}–10^{35} erg s^{-1}) compared to those of persistent MXRBs and which do not display outbursts. The X-ray source 4U 2206+54 is one of these objects.

It was discovered by *Uhuru* (Giacconi et al. 1972), was monitored with *EXOSAT* between 1983 and 1985 by Saraswat & Apparao (1992) who reported aperiodic hard flares from the source lasting a few hundred seconds and producing variations of a factor 3 to 5, and long-term variations of a factor of ~20 in the 2−10 keV persistent luminosity (≈0.3–5×10^{34} erg s^{-1}). These authors also reported a pulse period of ~400 s, which however has been recently questioned by Corbet & Peele (2001) from a re-analysis of the *EXOSAT* data as well as of archival *RXTE* data. Corbet & Peele (2001) further reported, on the basis of ASM observations, a 9.6-d periodicity in the X-ray flux of the source; they also modeled the *RXTE* spectra obtained on two occasions (March 11 and 13, 1997) using a power law modified with an exponential cutoff. They found a flux decrease by a factor of three (from 3.12×10^{-10} to 1.14×10^{-10} erg cm^{-2} s^{-1}) between the two pointings. Negueruela & Reig (2001) reanalyzed the *RXTE* pointing of March 11, 1997 obtaining comparable results; they also confirmed the presence of flares during which they found a positive correlation between source hardness and flux. These authors also did not detect any X-ray pulsation from the object.

The X-ray spectral characteristics of this source are typical of accretion onto a NS from a wind coming from the

⋆ Deceased.

Table 1. Log of the *BeppoSAX* observation presented in this paper.

Start day	Start time (UT)	Duration (ks)	On-source time (ks) LECS	MECS	PDS
1998 Nov. 23	16:02:49	66.6	12.6	33.6	15.2

companion star (Negueruela & Reig 2001), although the hypotheses of an accreting white dwarf (WD: Saraswat & Apparao 1992; Corbet & Peele 2001) or black hole (BH: Negueruela & Reig 2001) were also considered.

The optical counterpart was identified by Steiner at al. (1984) as the early-type star BD +53°2790, located at 2.5 kpc from the Earth. This star was subsequently thoroughly studied in its optical-UV spectroscopic properties by Negueruela & Reig (2001) who classified it as a peculiar late O-type active star. No radio counterpart has been detected so far (Nelson & Spencer 1988).

The information available on 4U 2206+54 is therefore not conclusive to understand the nature of the accreting source. In particular, the lack of knowledge of its X-ray spectrum above 30 keV hinders any hypothesis on the presence of a Cyclotron Resonant Feature (CRF) and thus any conjecture on the magnetic field of the accreting source as well as on its nature. Likewise, the poor sampling concerning the soft side of the X-ray spectrum never allowed an accurate estimate of the hydrogen column density $N_{\rm H}$; also, this did not allow a sensitive search for a soft component in the emission from this source. Moreover, a further independent check of the presence of a periodic variability (or the lack thereof) in X-rays is also needed.

Therefore, to explore the timing and spectral behaviour of 4U 2206+54 over a broad spectral range, with particular attention to both soft (<2 keV) and hard (>20 keV) X-ray domains, we observed this source with *BeppoSAX* (Boella et al. 1997a).

The paper is organized as follows: Sect. 2 will illustrate the observations and the data analysis, while in Sect. 3 the results showing the X-ray spectral and timing behaviours of 4U 2206+54 will be reported; in Sect. 4 a discussion will be given.

2. The *BeppoSAX* pointing

4U 2206+54 was observed between November 23 and 24, 1998, for a total on-source time of ~67 ks. The source was observed with three of the four coaligned Narrow-Field Instruments (NFIs) mounted on *BeppoSAX*: the Low Energy Concentrator Spectrometer (LECS, 0.1−10 keV; Parmar et al. 1997), two Medium Energy Concentrator Spectrometers (MECS, 1.5−10 keV; Boella et al. 1997) and the Phoswich Detection System (PDS, 15−300 keV; Frontera et al. 1997). The High-Pressure Gas Scintillation Proportional Counter (HPGSPC, 6−60 keV; Manzo et al. 1997) was temporarily not available between November 18 and 25, 1998: therefore, no data for 4U 2206+54 were obtained with this instrument. The total duration of this *BeppoSAX* pointing along with the on-source exposure times for each used NFI are reported in Table 1.

Good NFI data were selected from intervals outside the South Atlantic Geomagnetic Anomaly when the elevation angle above the earth limb was >5°, when the instrument functioning was nominal and, for LECS events, during spacecraft night time. The SAXDAS 2.0.0 data analysis package (Lammers 1997) was used for the extraction and the processing of LECS and MECS data. The PDS data reduction was instead performed using XAS version 2.1 (Chiappetti & Dal Fiume 1997). LECS and MECS data were reduced using an extraction radius of 6′ and 4′, respectively, centered at the source position; before extraction, data from the two MECS units were merged. Background subtraction for the two imaging instruments was performed using standard library files, while the background for the PDS data was evaluated from the fields observed during off-source pointing intervals.

Because 4U2206+54 is located near the Galactic plane and is not a particularly bright X-ray binary, we checked for possible effects induced by Galactic diffuse emission in the PDS data background evaluation. The off-source fields for background evaluation were indeed at different Galactic latitudes ($b = -4.^\circ0$ and $b = +1.^\circ6$) with respect to the source ($b = -1.^\circ2$), so a gradient in the Galactic diffuse emission could potentially be present. However, the count rate difference between the two fields is 0.07 ± 0.06 counts s^{-1}, thus consistent with zero; moreover, this difference impacts on the background estimate by less than 0.5%. Therefore we considered this effect negligible.

3. Results

3.1. Light curves and timing analysis

The 2−10, 2−5 and 5−10 keV MECS light curves of 4U 2206+54 as seen during the *BeppoSAX* pointing, background-subtracted and rebinned at 300 s, are displayed in Fig. 1. They show substantial random variability (up to a factor ~10 overall) in the form of repeated flares lasting ~1 h with internal fluctuations down to timescales of ~50−100 s.

To see if this erratic behaviour implied spectral changes depending on the source intensity, we computed a hardness ratio between the 5−10 keV and the 2−5 keV count rates and plotted it against the total 2−10 keV count rate. The results are shown in Fig. 2: apparently, there is no dependence of the hardness ratio on the total intensity of 4U 2206+54 in the 2−10 keV range. This result differs from the findings of Negueruela & Reig (2001) who found that the source became harder with increasing X-ray intensity during an *RXTE* pointing.

Timing analysis on the 2−10 keV data (i.e. where the *S/N* was highest) was performed with the FTOOLS v5.1[1] (Blackburn 1995) tasks `powspec` and `efold`, after having converted the event arrival times to the solar system barycentric frame. The results do not reveal the presence of any kind of periodicity or quasiperiodic oscillation. In particular, we did not detect the 392 s periodicity reported by Saraswat & Apparao (1992), thus confirming the negative findings of Corbet & Peele (2001) and Negueruela & Reig (2001). We get a 90% confidence level upper limit of ~8% in the amplitude of the signal

[1] Available at: `http://heasarc.gsfc.nasa.gov/ftools/`

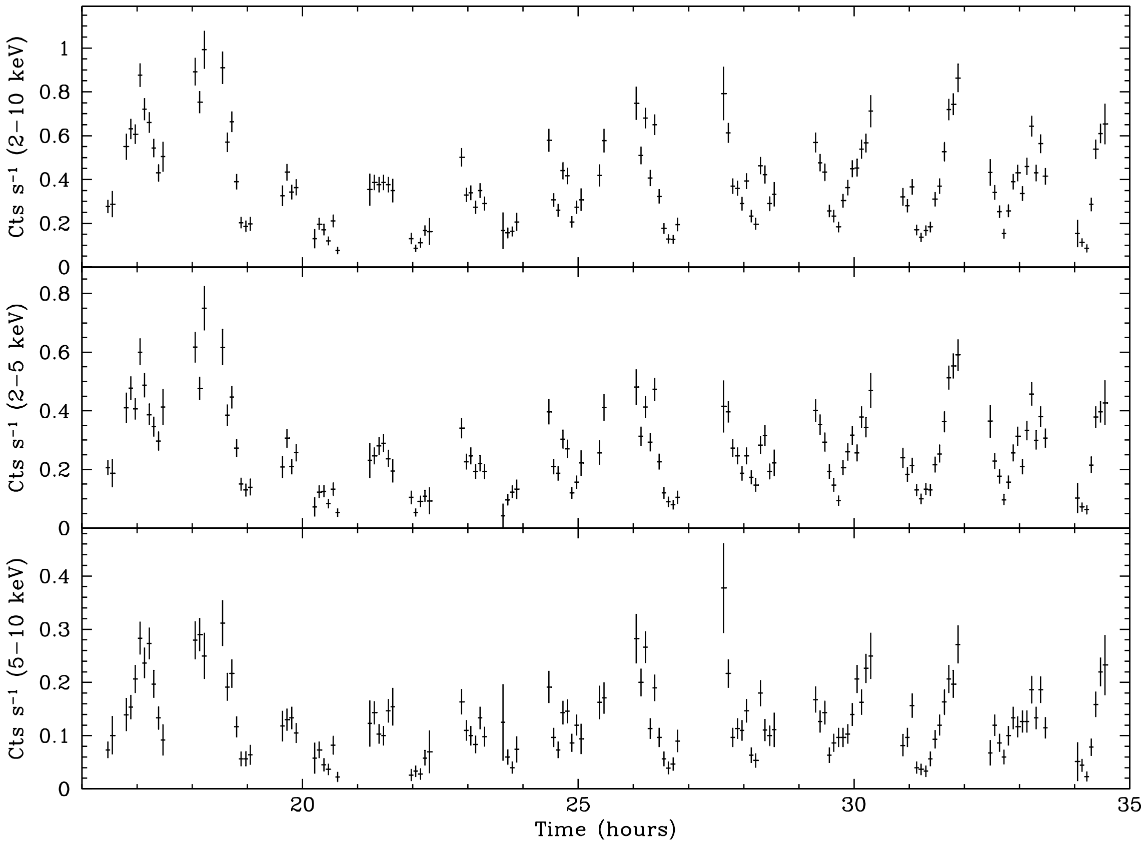

Fig. 1. Background-subtracted X-ray light curves of 4U 2206+54 in the 2−10 keV *(upper panel)*, 2−5 keV *(middle panel)* and 5−10 keV *(lower panel)* ranges as observed during the *BeppoSAX* pointing. All curves are rebinned at 300 s. Flaring activity on timescales of ∼1 h can be noticed. Times are expressed in hours starting from 00:00 UT of November 23, 1998. Vertical error bars show 1σ confidence level uncertainties for each bin.

in the 2−10 keV light curve induced by the above periodicity, consistent with the results of Corbet & Peele (2001).

The Power Spectral Density (PSD) obtained with this analysis is characterized by red noise and shows no significant deviations from the shot-noise behaviour, similarly to that found by Negueruela & Reig (2001). The rms variability of the 2−10 keV light curve is ∼40% in the 10^{-3}–1 Hz range, with no significant differences when only the softer (2−5 keV) or the harder (5−10 keV) band is considered, in agreement with the result, presented above, that no spectral dependence as a function of the total source intensity is found.

3.2. Spectra

To perform spectral analysis, the NFI pulse-height spectra were rebinned to oversample by a factor of 3 the full width at half maximum (*FWHM*) of the energy resolution and to have a minimum of 20 counts per bin, such that χ^2 statistics could reliably be used. Data were then selected, for each NFI, in the energy intervals in which sufficient counts were detected from the source and for which the instrument response function was well determined. This led us to consider the spectral interval 0.6−4 keV for the LECS, 1.8−10 keV for the MECS and 15−60 keV for the PDS. We then used the package XSPEC (Dorman & Arnaud 2001) v11.0 to fit the resulting broad band energy spectrum.

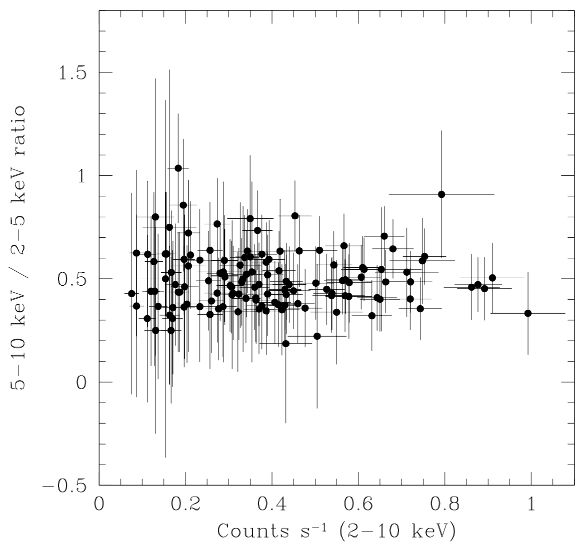

Fig. 2. Hardness-intensity diagram for 4U 2206+54 during the *BeppoSAX* pointing. No significant trend of the 5−10 keV/2−5 keV hardness ratio with increasing 2−10 keV intensity is found. Error bars show 1σ confidence level uncertainties for each point.

We included in all fits described here an interstellar photoelectric absorption column, modeled using the Wisconsin cross sections as implemented in XSPEC (Morrison & McCammon 1983) and with solar abundances as given by Anders & Grevesse (1989).

Table 2. Best-fit spectral parameters for 4U 2206+54. Quoted errors are at 90% confidence level for a single parameter. Quantities in square brackets are frozen at the indicated value. Luminosities, corrected for interstellar Galactic absorption, are computed assuming a distance d = 2.5 kpc and are expressed in units of 10^{34} erg s^{-1}.

	(1)	(2)	(3)	(4)
Parameter	PL+HighEcut	BrokenPL	BB+compST	BB+compST+CRF
χ^2/d.o.f.	245.0/219	233.3/219	228.9/218	225.0/217
$N_{\rm H}{}^a$	$0.88^{+0.21}_{-0.19}$	$0.86^{+0.20}_{-0.16}$	0.81±0.21	$0.77^{+0.20}_{-0.18}$
Γ	$0.95^{+0.11}_{-0.14}$	$0.99^{+0.10}_{-0.12}$	–	–
Γ_2	–	$2.03^{+0.12}_{-0.11}$	–	–
$E_{\rm cut}$ (keV)	$4.3^{+0.6}_{-0.5}$	5.6±0.4	–	–
$E_{\rm fold}$ (keV)	$10.6^{+2.7}_{-2.0}$	–	–	–
$N_{\rm PL}$ ($\times10^{-3}$)	3.6±0.6	$3.7^{+0.7}_{-0.5}$	–	–
$T_{\rm BB}$ (keV)	–	–	$1.63^{+0.12}_{-0.16}$	$1.61^{+0.10}_{-0.17}$
$R_{\rm BB}$ (km)	–	–	$0.15^{+0.03}_{-0.02}$	0.15±0.02
$T_{\rm e^-}$ (keV)	–	–	9^{+9}_{-3}	19^b
τ	–	–	9^{+5}_{-3}	7^{+3}_{-4}
$N_{\rm Comp}$ ($\times10^{-3}$)	–	–	3.3±1.1	$3.0^{+1.0}_{-0.8}$
$E_{\rm CRF}$ (keV)	–	–	–	[35]
$W_{\rm CRF}$ (keV)	–	–	–	[10]
$\delta_{\rm CRF}$	–	–	–	$1.4^{+1.6}_{-1.1}$
$L_{0.5-2\ {\rm keV}}{}^c$	0.65	0.67	0.67	0.63
$L_{2-10\ {\rm keV}}$	3.15	3.10	3.09	3.09
$L_{10-50\ {\rm keV}}$	3.01	3.95	3.74	3.50

^{a} In units of 10^{22} cm^{-2}.
^{b} Poorly constrained.
^{c} This value was computed by extrapolating the best-fit models down to 0.5 keV.

When performing the spectral fits, normalization factors were applied to LECS and PDS spectra following the cross-calibration tests between these instruments and the MECS (Fiore et al. 1999). These factors were constrained to be within the allowed ranges during the spectral fitting.

The *BeppoSAX* data (Figs. 3 and 4) clearly show continuum emission both above 30 keV and below 1 keV. To the best of our knowledge this is the first time that X-ray emission outside the 1−30 keV range is reported from this source.

Motivated by the results obtained in Sect. 3.1, and to further test the dependence (or lack thereof) of the 4U 2206+54 spectral shape on the total source intensity, we created two time windows: one in which the source was above 0.3 counts s^{-1} in the 2−10 keV band ("high state") and the other characterized by the source being below 0.3 counts s^{-1} ("low state") in this energy range. We then accumulated the spectra over these two windows and compared them by using the best-fit models in Table 2 (see the analysis of time-averaged spectra below). As expected, given the results in Sect. 3.1, no significant parameter variations (with of course the exception of the model normalizations) were found between these high- and low-state spectra of 4U 2206+54 for any of the tested best-fit models.

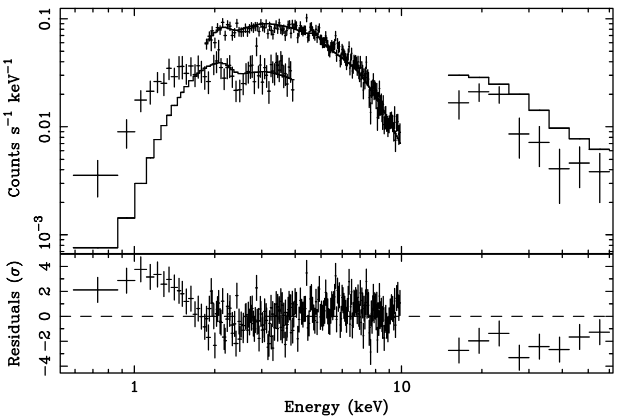

Fig. 3. Average 0.6−60 keV X-ray spectrum of 4U 2206+54 obtained with the *BeppoSAX* NFIs and fitted with a photoelectrically absorbed PL. The best-fit model is shown as a continuous line. Clearly, this model (with a reduced χ^2 = 1.7) does not provide an acceptable description of the spectral data, particularly below 2 keV and above 10 keV, as seen in the panel reporting the residuals.

We therefore considered the average spectrum of 4U 2206+54 given that no hints of variation in the spectral shape during the *BeppoSAX* pointing were suggested by the inspection of the color-intensity diagram of the source

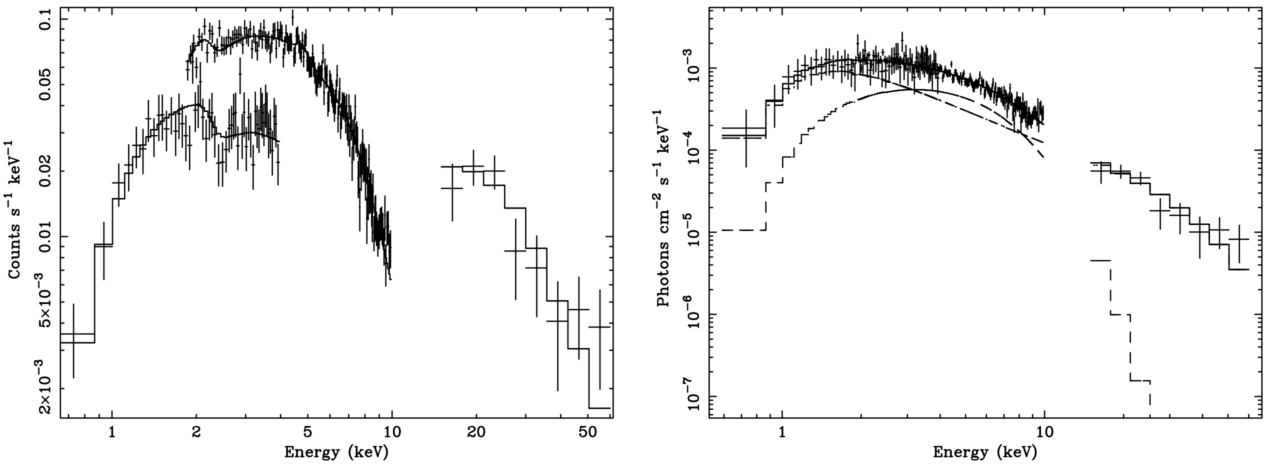

Fig. 4. *Left panel*: average 0.6−60 keV X-ray spectrum of 4U 2206+54 obtained with the *BeppoSAX* NFIs and fitted with a photoelectrically absorbed BB plus Comptonization. The best-fit model is shown as a continuous line. *Right panel*: unfolded *BeppoSAX* photon spectrum fitted with this same model. The two components are indicated with short-dashed (BB) and long-dashed (Comptonization) lines, while the overall model is again indicated with a continuous line.

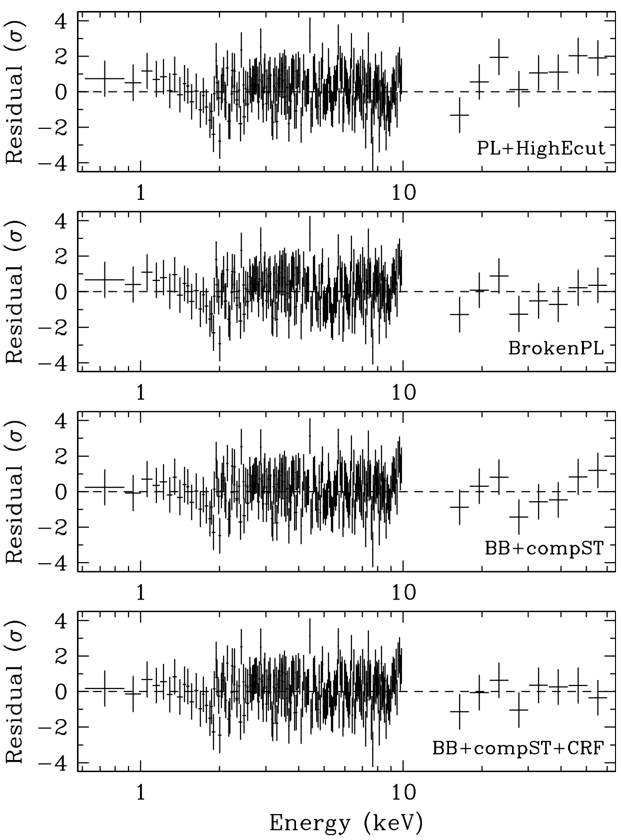

Fig. 5. Comparison among the residuals obtained with the best-fit models listed in Table 2. Names associated with each panel refer to Cols. 1–4 of this table.

(reported in Fig. 2). Table 2 reports the models and parameters thereof that best fit the spectral data. Figure 5 shows instead the data residuals associated with each of the best-fit model presented in Table 2.

A possible concern in considering the average spectrum might rise from the fact that, during the *BeppoSAX* observation, the source was strongly variable; the NFIs may thus have sampled different subsets of the light curve during the pointing. This could have introduced spurious spectral distortions. However, given that the intercalibration factors among the three instruments were in the allowed ranges even when they were left free to vary during the spectral fits, we are confident that this did not produce any effect on the averaged *BeppoSAX* spectrum.

We first tried to fit the overall 0.6−60 keV spectrum of 4U 2206+54 detected by the *BeppoSAX* NFIs by using a simple power law (PL). The results, as shown in Fig. 3, are clearly unsatisfactory, with a reduced χ^2 = 1.7, an excess at low energies below 2 keV and a deficit at high energies above 10 keV. So we applied the phenomenological model made of a PL modified by a high-energy exponential cutoff. This is considered the "classical" way of describing the X-ray spectra of MXRBs (e.g., White et al. 1983a). As in Negueruela & Reig (2001), an acceptable fit − see Col. 1 of Table 2 – was obtained.

A similarly good fit, as reported in Col. 2 of Table 2, was also achieved using a broken PL. Other simple models such as blackbody (BB), disk-blackbody (DBB; Mitsuda et al. 1984) and thermal bremsstrahlung (TB) provided instead poor fits.

We then tried to fit the spectrum by using a more physical description. Given that simple models failed, we tried a composition of two models. The best results were obtained considering a BB plus a Comptonization model. For the latter, we used the first-order modelization by Sunyaev & Titarchuk (1980; compST in xspec). In this case also, an acceptable fit was achieved; this case is shown in Fig. 4, and its parameters are in Col. 4 of Table 2. The fit a DBB instead of a BB makes the compST parameter τ unconstrained.

A description of the *BeppoSAX* spectrum made by using the more accurate and complex Comptonization model by Titarchuk (1994; compTT in xspec), with either the addition of a BB or not, failed to provide a sound value of $N_{\rm H}$: this was always unacceptably (i.e., up to two orders of magnitude) lower than the Galactic one, which is $N_{\rm H}^{\rm G}$ = 0.59 × 10^{22} cm^{-2} according to Dickey & Lockman (1990); this model could not constrain all the Comptonization (and BB, if present) parameters. Nonetheless, the best-fit values of the compTT parameters were consistent with those obtained from the Comptonization component in the best-fit BB+compST model listed in Table 2: this suggests that the failure of the compTT model is more likely due to its complexity compared to the overall quality of the spectrum, rather than to a completely wrong description of the source spectral shape. In this case also, the addition of a DBB to the compTT makes the model even more unstable.

We also performed a fit of the data with the xspec models raymond, mekal and vmekal, which describe the emission from a hot diffuse gas (Raymond & Smith 1977; Mewe et al. 1985). All these descriptions provided a poor description of the overall spectral shape (that is, returning a reduced $\chi^2 \sim 1.5$ in all cases), as already noted by Negueruela & Reig (2001) from the analysis of *RXTE* data. We note that, by adding a BB with $kT_{\rm BB} \sim 1.6$ keV to any of these models, the fit becomes formally acceptable; in this case, however, the temperature of the emitting diffuse gas is uncomfortably large (>60 keV) and unconstrained. So we consider this spectral modelization not viable. A similar result was obtained when considering a BB+TB model.

An attempt to use complex absorbers to describe the low-energy part of the spectrum was also made, given that 4U 2206+54 may be a system in which part of the absorption is intrinsic (Negueruela & Reig 2001). However, fits performed with a partial covering absorber did not improve the spectral description and did not allow us to constrain either the additional $N_{\rm H}$ or the covering percentage (around $5-6 \times 10^{22}$ cm^{-2} and 60−65%, respectively). The use of an ionized absorber instead of a neutral one did not produce any significant difference in the fit results. These findings were practically independent of the chosen basic model (Comptonization or PL).

No evidence for an iron emission line around 6.5 keV was found: we obtained upper limits (at 90% confidence level) to the equivalent width of <56 eV, <65 eV and <156 eV to the equivalent width in case of a line with narrow (0.1 keV), broad (0.5 keV) and very broad (1 keV) *FWHM*, respectively. These values are largely independent of the chosen best-fit model.

Following the suggestion by Corbet & Peele (2001) we then tried to look for a signature of a highly magnetic field NS, through the search for a CRF in absorption, in the high-energy part of the *BeppoSAX* spectrum. To do this, we used the cyclabs multiplicative model (Mihara et al. 1990; Makishima et al. 1990) in xspec. The limited *S/N* ratio above 15 keV prevented us from fully exploring this possibility; however, to limit the number of free parameters introduced by this addition to the spectrum description, we chose to freeze the line energy and width. The latter was fixed to a value typical of magnetic NSs in MXRBs, i.e. 10 keV (e.g. Orlandini & Dal Fiume 2001), while we made the former vary between 10 and 60 keV in steps of 5 keV among the fits. We found that only in the case of the BB+compST model a CRF with a best-fit line energy of 35 keV was justified – see Col. 4 of Table 2 –, albeit at a 2σ confidence level only, according to the results obtained by running an F-test. The other best-fit models in Table 2 (broken PL and high-energy cutoff PL) are not improved by the addition of a CRF. Thus, given all the assumptions and the uncertainties described above, we regard this CRF identification as tentative only.

Assuming a distance to 4U 2206+54 of 2.5 kpc (Steiner et al. 1984) and using the models described above for the average spectrum of the source, we can evaluate the unabsorbed luminosities of the source in the 0.5−2 keV, 2−10 keV and 10−50 keV bands for each best-fit model. These values are reported in Table 2. The ratios between the BB and Comptonization contributions in the BB+compST model in the three X-ray bands above are 0.17, 1.98 and 0.07, respectively.

4. Discussion

The *BeppoSAX* observation of 4U 2206+54 reported in this paper allowed us to study the properties of the source in great detail, and for the first time, in the 0.6−60 keV range. The source exhibited an average 2−10 keV unabsorbed luminosity of 3.1×10^{34} erg s^{-1} during this pointing, thus comparable with the "high-state" emission observed by Saraswat & Apparao (1992) in 1983 and 1985 from *EXOSAT* data, but ∼10 times brighter than that observed by these authors in 1984, and a factor ∼10 fainter than during the 1997 *RXTE* pointing (e.g., Negueruela & Reig 2001). Thus the source can vary by about 10 fold, and as much as a factor of ∼100, on year-long timescales. This can also be seen in Fig. 1 of Corbet & Peele (2001), where the entire *RXTE*/ASM 1.5−12 keV light curve of 4U 2206+54 between years 1996 and 2001 is shown. The periodogram in Fig. 2 of these authors shows a peak at a frequency of $\approx 4 \times 10^{-3}$ d^{-1}: if real, this would indicate the presence of a further (superorbital?) periodicity of ≈250 d in the system.

On much shorter time scales, the 2−10 keV light curve shows flares of remarkable (a factor ten) intensity variations lasting about 1 h, with finer variability down to timescales of 50−100 s. This flaring emission does not appear to imply spectral variation correlated with the intensity. Moreover, the PSD analysis indicates that the variable X-ray emission from the source is due to a stochastic phenomenon. These long- and short-term variability characteristics point to an explanation for this X-ray activity as due to random inhomogeneities in the accretion flow onto a compact object (e.g. van der Klis 1995).

The colorless variability result obtained from our *BeppoSAX* data is at odds with that found by Saraswat & Apparao (1992) and by Negueruela & Reig (2001). The explanation for this is not clear. Concerning the findings by Saraswat & Apparao (1992) this discrepancy can be due to slight secular variations of the source hardness ratio in observations separated in time by about two years: indeed, if one considers the 1983 and 1985 *EXOSAT* data in their Fig. 4 separately, no significant hardness-intensity dependence is observed. As regards instead the discrepancy with the data from the *RXTE* pointing in Negueruela & Reig (2001) it may be possible that this hardness-intensity dependence becomes more evident at larger source luminosities.

Moreover, the PSD of *BeppoSAX* data does not show any periodicity in the 10^{-3}–1 Hz range. We thus independently confirm the results by Corbet & Peele (2001) and Negueruela & Reig (2001) that no ≈400 s X-ray modulation comes from 4U 2206+54.

X-ray spectroscopy with *BeppoSAX* can help us in better understanding the accretion dynamics as well as the nature of the accretor. Indeed, we obtained for 4U 2206+54 an unprecedented simultaneous spectral coverage of the 0.6–60 keV range. Our results show that the "classic" model generally used to fit the X-ray spectra of MXRBs hosting an accreting NS (White et al. 1983a) works very well, as in the case of the March 1997 *RXTE* data. In these observations the spectral parameters $N_{\rm H}$, Γ, $E_{\rm cut}$ and $E_{\rm fold}$ were in the range 1.12–1.71, (2.7–4.6) $\times$ 10^{22} cm^{-2}, 5.3–7.3 and 10.5–17.3, respectively, with the values at the lower edge of the interval holding at low source fluxes (Corbet & Peele 2001).

However, when we compare our best-fit parameters with the *RXTE* spectral findings obtained when the source flux was highest (corresponding to a 2–10 keV luminosity of 2.3 $\times$ 10^{35} erg s^{-1}), we see that in our data (i) the spectral slope Γ is substantially harder; (ii) both characteristic energies of the model, $E_{\rm cut}$ and $E_{\rm fold}$, are lower by a factor $\sim$2; (iii) the hydrogen column density $N_{\rm H}$ is lower by a factor $\sim$6. Comparison with the lower-intensity *RXTE* observation (which implies a 2–10 keV luminosity of 8.5 $\times$ 10^{34} erg s^{-1}) shows a consistency with the *BeppoSAX* data barring the $N_{\rm H}$ value, which is still $\sim$3 times higher in the *RXTE* results.

The results of points (i) and (ii) above may reflect an actually different spectral shape due to a different emission level from the source with respect to that observed in the March 1997 *RXTE* data. Indeed, Table 1 of Corbet & Peele (2001) shows that Γ (which they indicate as α in their paper), $E_{\rm cut}$ and $E_{\rm fold}$ appear to inversely correlate with the source flux, and a simple computation indicates that the source gets harder as the flux increases. Therefore, it appears that there is a switch to harder source spectra when 4U 2206+54 overcomes a threshold luminosity with a value lying somewhere between 1 $\times$ 10^{35} and 2 $\times$ 10^{35} erg s^{-1}. Unfortunately, in the light of the above data, we cannot say if this transition occurs smoothly or in the form of a "parameter jump".

Instead, we believe that the $N_{\rm H}$ measurement obtained with *BeppoSAX* is substantially different and more reliable thanks to the better spectral coverage at low energies afforded by the *BeppoSAX* LECS. Indeed, if we consider only our data above 2.5 keV, we obtain that $N_{\rm H} = 2.5^{+0.9}_{-1.0} \times 10^{22}$ cm^{-2}. Thus, in our opinion the $N_{\rm H}$ value obtained with *BeppoSAX* should be considered as the correct one. We note that the order-of-magnitude difference in flux between the *BeppoSAX* and the *RXTE* 2–10 keV measurements cannot be explained by the different $N_{\rm H}$ estimate, which at most may account for a flux difference of about 30% only.

This new value of $N_{\rm H}$, (0.8–0.9) $\times$ 10^{22} cm^{-2}), compares much better with the Galactic value along the 4U 2206+54 line of sight (0.59×10^{22} cm^{-2}) and with the optical V-band reddening value (A_V = 1.6) given by Negueruela & Reig (2001): although the empirical relation between A_V and $N_{\rm H}$ by Predehl & Schmitt (1995) implies the presence of further hydrogen local to the source, the difference is now to within a factor of two, and not an order of magnitude as from the previous $N_{\rm H}$ estimates. This alleviates the conundrum, stressed by Negueruela & Reig (2001), of the non-detection of iron emission in presence of very optically thick material around the X-ray source. Concerning this issue, our observation allowed us to put tighter upper limits on the presence of any X-ray Fe emission with respect to the one determined by *EXOSAT* (Gottwald et al. 1995).

The spectrum description by means of a more physically sound model, namely a BB+Comptonization, again points to the presence of a very compact object as the accretor: the spectral shape and the temperatures of the BB and the Compton cloud would suggest that the system most likely harbours a NS. Indeed, the presence of a WD in 4U 2206+54 is basically ruled out because of the X-ray spectral shape, which is completely different from that observed by e.g. Kubo et al. (1998) and Owens et al. (1999) in the system γ Cas, which is thought to host a WD. A better comparison between 4U 2206+54 and systems hosting a WD might come if we consider magnetic cataclysmic variables, such as intermediate polars (see e.g. de Martino et al. 2004 and references therein). However, these objects have spectra with a BB temperature $\approx$30 times lower than found in 4U 2206+54, and practically no emission detectable above 30 keV. Thus, the high BB temperature of 4U 2206+54 is not compatible with that of a WD surface, which is expected to mainly emit in the UV rather than in the soft X-rays; additionally, the detection of X-ray emission up to 60 keV can hardly be explained by assuming a WD as the accretor in this system.

The same line of thought applies to disfavour a BH interpretation: the Comptonization component has a temperature and an optical depth unusual for a BH in its low-hard state and hosted in a MXRB (e.g. Frontera et al. 2001). So, all the above points to a NS as the accreting object in this system, even if no pulsations were ever detected.

Several observed properties of the source are naturally explained by the accreting NS model. Concerning the X-ray luminosity, accretion onto the NS from a stellar wind emitted by the O9.5V companion star can easily fit the observations: following Frank et al. (1992), if we assume that the companion emits $\approx 10^{-6}$ $M_\odot$ in the form of a wind, one needs to hypothesize an accretion efficiency $\eta_{\rm acc} \approx 10^{-5}$ to produce a luminosity $L \approx 10^{35}$ erg s^{-1}. This value of $\eta_{\rm acc}$ may possibly be on the low side of the allowed values for accretion from stellar wind in close systems; however, according to Perna et al. (2003), if corrections to the standard formulae used to estimate the wind accretion rates are introduced, the accretion efficiency drops substantially.

Alternatively, as already suggested by Corbet & Peele (2001), partial accretion inhibition due to the "propeller effect" (Illarionov & Sunyaev 1975; Stella et al. 1986), according to which the magnetosphere of the NS acts as a barrier to accretion of matter onto the NS surface, can be at work. A fraction of the wind matter can nonetheless flow along the magnetic field lines and eventually can reach the NS surface.

As regards the secular X-ray variability over a timescale of $\approx$1 year, we suggest that this might be due to modulations in the wind density, such as density waves produced by pulsations of the companion star envelope.

In spite of all the above, the NS interpretation rises some problems. In particular, as it evidently appears from Table 2, the BB radius. Clearly, a size of $\sim$150 m is not acceptable if we assume that the whole NS surface is responsible for the

BB X-ray emission. In order to correct for approximations in the BB model application to X-ray data, the hardening factor f (Shimura & Takahara 1995), defined as the ratio between the color and the effective BB temperatures, can be introduced. This leads to a corrected BB radius equal to $f^2 \cdot R_{\rm BB}$. However, we should assume that $f \sim 8$ to regain the correct BB size for a NS (~10 km), while common values for f are around 1.7 (Merloni et al. 2000) and extremes do not exceed ~3 (Borozdin et al. 1998). A further possible explanation for the small BB emitting area size, assuming isotropic emission from the NS surface, is the following: because of cooling and backwarming effects the spectrum at the NS surface, if fitted with a "classic" BB model, can lead to the net result of underestimating the emitting area by as much as 2 orders of magnitude (London et al. 1986).

The alternative to solve this shortcoming is to assume that the emission is not isotropic, i.e. that the accreting matter is either forming a disk around the compact object or is funneled onto the NS magnetic polar caps.

The first possibility appears unlikely because accretion in this system is most probably occurring via stellar wind emitted from the companion star. This comes from assuming that the 9.6 d periodicity determined by Corbet & Peele (2001) is the orbital period of the system and that the masses of the two components are 1.4 $M_\odot$ for the NS and $M_* = 19\ M_\odot$ (Lang 1992) for the O9.5V companion, as spectroscopically identified by Negueruela & Reig (2001). With these values, the Roche lobe radius of the companion is $R_{\rm L} \sim 32\ R_\odot$, thus much larger than the radius of a O9.5V star, which is $R_* \sim 7.8\ R_\odot$ (Lang 1992). Thus, because the wind has very low intrinsic angular momentum, a large accretion disk is unlikely to be formed with this accretion mechanism. As remarked in the previous section, the use of a DBB model instead of a BB produces more unstable fits to our X-ray dataset.

Alternatively, a magnetically-driven accretion scenario can be considered: in this case, one needs the magnetic field of the compact object to be strong enough to form two accretion columns. Indeed, the tentative detection of a CRF indicating the presence of a $\approx 10^{12}$ Gauss magnetic field (see Orlandini & Dal Fiume 2001) associated with the NS would suggest this possibility.

A further indication that the BB emission is indeed anisotropic (i.e., confined on a fraction of the NS surface) comes from the estimate of the size $r_{\rm seed}$ of the region emitting the Comptonization seed photons. Following the prescription by in 't Zand et al. (1999) for the computation of $r_{\rm seed}$ and assuming that the Comptonization seed photons in 4U 2206+54 are produced by the BB (therefore $kT_{\rm seed} \sim 1.6$ keV) we obtain that $r_{\rm seed} \sim 0.12$ km. This estimate is in quite good agreement with our independent determination of the BB emission region radius (see Table 2), thus suggesting that indeed the BB emitting area covers only a fraction of the NS surface.

However, as no X-ray pulsations are detected from this source, the magnetically-driven accretion interpretation needs at least one of the following possibilities to be tenable: an angle between NS spin and magnetic axes close to zero, or a very low inclination angle for the system. In this latter case, even if we assume a non-zero but small (e.g., few degrees) angle between the NS magnetic field and spin axes, the system geometry is such that we could continuously see X-ray radiation from a single polar cap of the NS. Clearly, the emission will not be modulated by the NS rotation in this case also.

This of course means introducing a fine tuning of the system parameters: however, a similar scenario has been proposed to explain the absence of pulsations from 4U 1700−37 (White et al. 1983b) and, more recently, from 4U 1700+24 (Masetti et al. 2002), which are believed to host an accreting NS. For 4U 1700+24 Galloway et al. (2002) further supported this description by finding a small amplitude (1 km s^{-1}) Doppler periodicity of ~400 d in their optical spectroscopic data: this period, earlier suggested by Masetti et al. (2002) from timing analysis of *RXTE*/ASM data, is quite likely produced by the orbital motion of the system.

A test for the low-inclination hypothesis of 4U 2206+54 can come by determining, or at least by putting tight constraints on, the orbital Doppler shift of the companion star: indeed, assuming the system parameters discussed above, we find that the orbital velocity of the companion is $v_{\rm orb} \sim 20$ km s^{-1}; we note that this value is consistent with the scatter of the system radial velocities measured by Abt & Bautz (1963) from optical spectra.

Thus, summarizing, and despite the problems encountered in the analysis of the observational data on this source, the picture emerging is that 4U 2206+54 is a low-luminosity system composed of a NS and a "normal" blue main-sequence star; the NS is accreting from the wind coming from the companion and is orbiting it in a possibly low-inclination orbit. Tentative evidence of a strong magnetic field from the NS is found, but deep spectroscopic observations, e.g. with *INTEGRAL*, of the hard X-ray tail of this source are needed to confirm (or disprove) this. Long-term variations in the X-ray flux from the source can be explained as due to oscillations in the wind density, possibly induced by slow pulsations of the companion star envelope. This hypothesis can be tested with long-term spectrophotometric monitoring of the optical counterpart.

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