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Letter to the Editor

Detection of a broad iron emission line and sub-millisecond quasiperiodic oscillations from the type I X-ray burster 4U 1728-34 in a high state

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Abstract. We report results from simultaneous RossiXTE and BeppoSAX observations of the neutron-star x-ray binary and type I X–ray burster 4U 1728-34. The source was found in a high luminosity state, $L_X \sim 0.1 L_{\rm Edd}$, and quasiperiodic oscillations were detected at 1284 ± 6 Hz, the highest frequency ever observed from this source. The x-ray spectrum shows a broad, $\rm FWHM \sim 0.8$ keV, iron K_α fluorescence line. We discuss interpretations of the broad line and the quasiperiodic oscillations and how future simultaneous spectral and timing observations can be used to test these interpretations and, potentially, to estimate the mass of the compact object.

Key words: accretion, accretion disks – stars: individual: – stars: neutron – X-rays: stars

1. Introduction

The behavior of accretion flows around compact objects in x-ray binaries is of great interest for probing strong gravitational fields and for understanding the nature of compact objects. Two tools used in this pursuit are x-ray spectroscopy and x-ray timing. Both have proved useful, but ambiguities remain in the interpretation of either spectroscopic or timing observations. Combination of simultaneous timing and spectroscopic data may place stronger constraints on the properties of the accretion flow and on the compact object.

Here, we combine the timing capabilities of the Rossi X-ray Timing Explorer (RXTE; Bradt, Rothschild, & Swank 1993) with the wide spectral range and good spectral resolution of BeppoSAX (Boella et al. 1997) in an observation of the neutron-star low-mass x-ray binary (NS-LMXB) and type I x-ray burster 4U 1728-34 made simultaneously with the two observatories. Discovered by Uhuru (Forman et al. 1978), 4U 1728-34 is a well known persistent atoll source that shows frequent type I X-ray bursts (Basinska et al. 1984). The source shows line emission (White et al. 1986), kilohertz quasiperiodic oscillations (QPOs) in the persistent emission, and oscillations near 363 Hz in x-ray bursts (Strohmayer et al. 1996).

Our observations, as described in §2, found the source in an unusually luminous state. The timing analysis, including detection of quasiperiodic oscillations, is described in §3, and the spectral analysis, including detection of Fe line emission, in §4. We interpret these results in §5 and conclude, in §6, with a suggestion of a means via which future observations could be used to test the interpretation.

2. Observations and source state

4U 1728-34 was jointly observed by BeppoSAX from 1999 August 19, 01:57:29 UT to August 20 04:54:32 UT for a total on–source observing time of 51.3 ks and by RXTE from 1999 August 19 03:49:57 UT to August 20 11:26:15 UT for a total good observing time of 48 ks. Several x-ray bursts were detected during these observations. As we are interested here in the persistent emission, intervals of the observations surrounding the bursts were removed.

The RXTE data were used to determine the source state, i.e. location in the color-color diagram, and to study the timing behavior. We extracted x-ray colors in 256 s intervals from our observation and also, for comparison, from a large data set extracted from the RXTE archive, see Fig. 1. We selected energy bands of 2.6–4–6.4–9.7–16 keV to define the colors. The lower limit of our energy range is somewhat higher than typically used previously (Mendez & van der Klis 1999) because recent gain changes in the Proportional Counter Array (PCA; Zhang et al. 1993) do not allow reliable extraction of flux below 2.6 keV.

Source position within the color-color diagram changes continuously along a one-dimensional curve embedded in the two-dimensional diagram and position along the curve is generally thought to be an indicator of mass accretion rate within the system (Hasinger & van der Klis 1989; Schulz, Hasinger & Trumper 1989). For the colors chosen in

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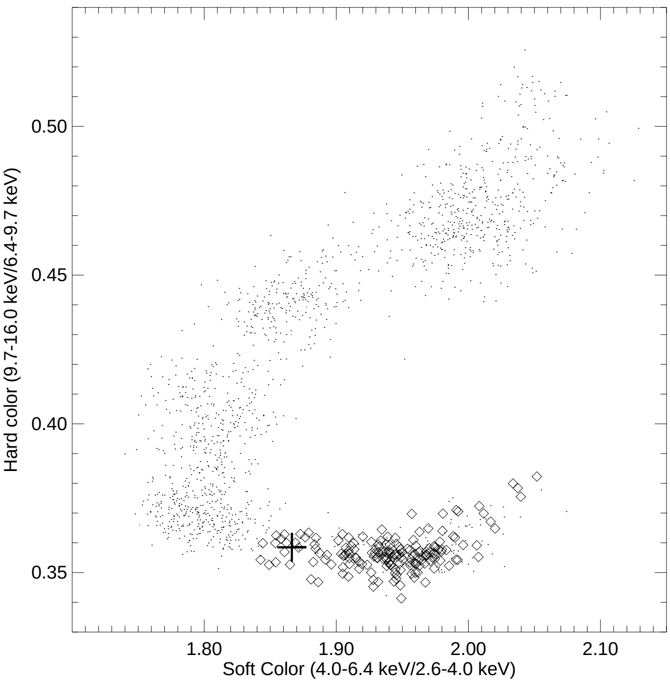

Fig. 1. A color-color diagram for 4U 1728-34. The points represent 256 s intervals of data from previous RXTE observations. The diamonds represent intervals from the observation analyzed here. The cross indicates the colors during the interval when the QPO (see text) was detected.

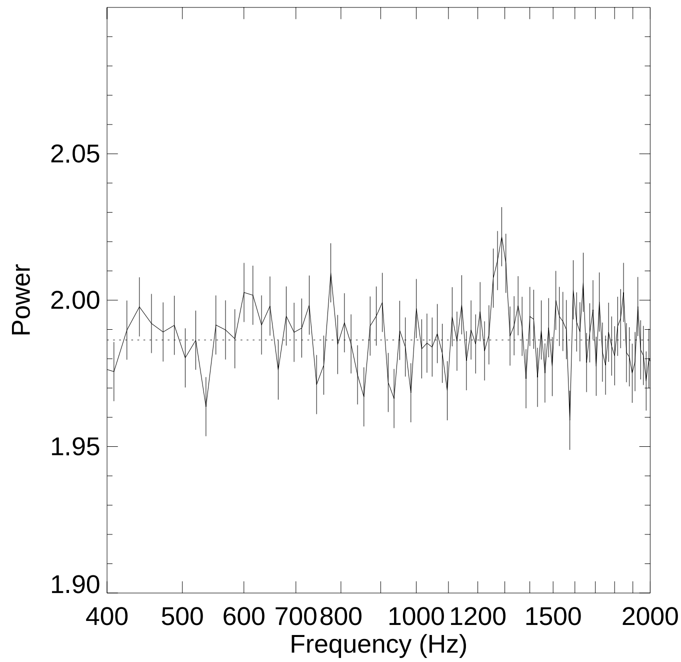

Fig. 2. Power spectrum for the 2460 s interval containing the QPO at 1284 ± 6 Hz. The powers are Leahy normalized and have been rebinned for presentation. The dotted line shows the calculated Poisson noise level.

Fig. 1, mass accretion rate increases as the curve is traversed counterclockwise. From the position of the source in the color-color diagram, we infer that the source was in a state of high mass accretion rate during the observations analyzed here.

3. Timing behavior

We searched for QPOs in the range 400–2000 Hz in intervals of continuous observation, summing 2 s power spectra calculated from $122\,\mu$s time resolution PCA event data within each interval. We first conducted a search over 256 s intervals using all events, but did not find any significant QPO peaks. Previous QPO searches using relatively short intervals in observations of 4U 1728-34 have shown that the QPO amplitudes drop below the threshold of detection at high inferred mass accretion rates (Mendez & van der Klis 1999), such as found during our observation. Thus, this null result was not unexpected.

From analysis of archival observations at the highest inferred mass accretion rates where kHz QPOs were detected, we found that selection of events with energies above 4 keV optimized the signal to noise ratio for detection of kHz QPOs. We used this energy selection criterion to perform a new kHz QPO search in the current data. To maximize the statistics available in each power spectrum, we used full continuous observation intervals with typical durations near 3 ks. The only detection of a significant kHz QPO peak in our search range (400–2000 Hz) in our data is of a QPO peak at 1284 ± 6 Hz in an interval with a duration of 2460 s, see Fig. 2. The QPO peak has a width of $32 \pm 12\,\mathrm{Hz}$ and an rms amplitude of $3.9\% \pm 0.5\%$ (above 4 keV). Allowing for 75 trials, we estimate the probability of chance occurrence to be 1.5×10^{-5}, corresponding to a 4.3σ detection.

The QPO frequency is the highest ever reported for 4U 1728-34. In 4U 1728-34, the frequency of kHz QPOs is well correlated with position in the color-color diagram with higher frequencies corresponding to higher inferred mass accretion rates (Mendez & van der Klis 1999). The x-ray colors during the interval when the QPO is detected (1.866, 0.358) are indicated by the cross in Fig. 1 and correspond to a higher inferred mass accretion rate than any previous kHz QPO detection in this source.

4. Spectral behavior

Broad band energy spectra of the source were obtained combining data from the four BeppoSAX Narrow Field Instruments (NFIs): the Low Energy Concentrator Spectrometer (LECS; Parmar et al. 1997) for 0.3–4 keV, the Medium Energy Concentrator Spectrometer (MECS; Boella et al. 1997) for 1.8–10 keV, the High Pressure Gas Scintillation Proportional Counter (HPGSPC; Manzo et al. 1997) for 8–40 keV, and the Phoswich Detection System (PDS; Frontera et al. 1997) for 15–50 keV. LECS and MECS data were extracted in circular regions centered on the source position using radii of 8' and 4' respectively, containing 95% of the source flux. An image analysis of the BeppoSAX data revealed no other sources. There is a source in the WGACAT (White, Giommi, & Angelini 1994) $5'$ away, but its flux is a factor of 100 lower and would not significantly contaminate the spectra. The spectra have been rebinned

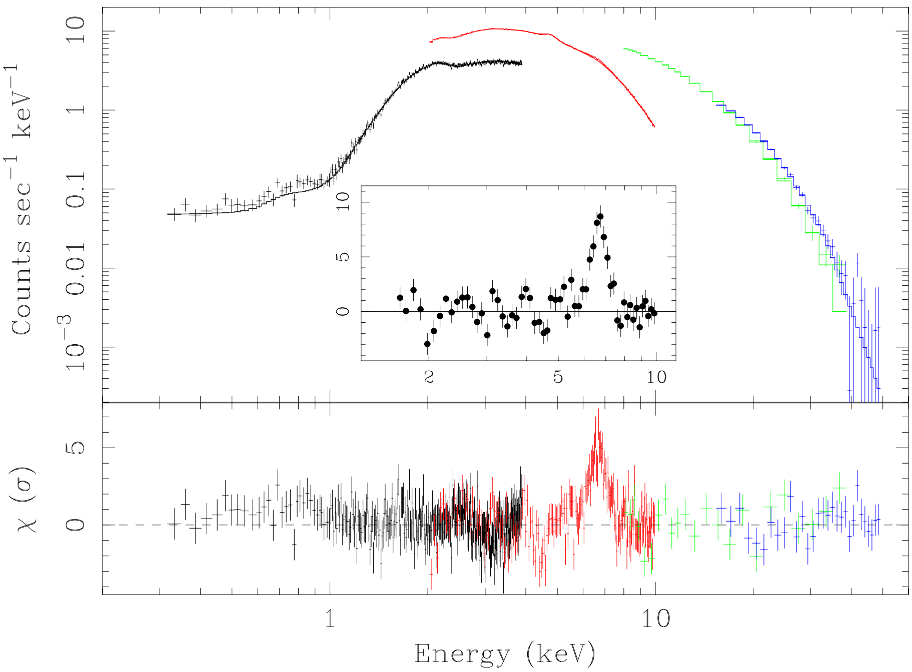

Fig. 3. The 0.1-50 keV spectrum of 4U 1728-34 observed by BeppoSAX is shown together with the residuals in the entire band, in unit of standard deviations, when the best fit continuum is applied in the whole band except the 4–8 keV energy range. The inset shows the residuals of the MECS data rebinned to better display the profile of the observed Fe K_α feature.

Table 1. Spectral parameters of 4U 1728-34.

Parameter	Value
kT_γ[keV]	1.16 ± 0.03
kT_e[keV]	3.16 ± 0.03
τ	11.4 ± 0.2
$kT_{\rm bb}$[keV]	0.57 ± 0.01
$F_{\rm bb}[10^{-9}\,{\rm erg\,cm^{-2}\,s^{-1}}]$	2.18 ± 0.05
$E_{\rm G}$[keV]	6.72 ± 0.05
σ[keV]	0.34 ± 0.08
EW[eV]	52 ± 9
$N_{\rm H}[10^{22}{\rm cm^{-2}}]$	2.73 ± 0.05

Note — All quoted errors represent 90% confidence level for a single parameter.

to have at least 30 counts per channel, and the HPGSPC and PDS spectra were grouped using a logarithmic grid. Standard normalization factors have been included to account for the mismatch in the BeppoSAX instruments absolute flux calibration. We found that spectra extracted for different intervals within the observations gave spectral parameters consistent within errors. Thus, we report spectral fits only for the sum over the entire BeppoSAX observation.

Different models were used to fit the broad band continuum. The one that gave the best fit contained the following components: 1) a black body at soft energies (White et al. 1988) described by a temperature ($kT_{\rm bb}$) and flux ($F_{\rm bb}$), 2) a Comptonized component (COMPTT, Titarchuk 1994) for the hard energy part described by the temperature of injected photons (kT_γ), the electron temperature (kT_e), and optical depth (τ), 3) photoelectric absorption at low energy with a column density ($N_{\rm H}$). However, even this model alone was clearly rejected, $\chi^2_\nu \sim 1.65$, and strong residuals were present between 4 and 8 keV indicative of Fe line emission. In order to find the best fit continuum parameters, we fitted the continuum excluding the data between 4 and 8 keV. In Fig. 3, the spectrum together with residuals from this fit are shown. The line emission is clearly broader than the instrumental response ($\sigma = 0.20\,{\rm keV}$ at 6 keV); using a single narrow line in place of the broad line increases the χ^2 by 30. The line was modeled adding a simple Gaussian profile with centroid ($E_{\rm G}$), width (σ), and equivalent width (EW). The best fit had $\chi^2/{\rm DoF} = 653/516$ and the best fit parameters are reported in Table 1. The 0.2-50 keV flux was $6.4 \times 10^{-9}\,{\rm erg\,cm^{-2}\,s^{-1}}$ and the unabsorbed flux was $8.6 \times 10^{-9}\,{\rm erg\,cm^{-2}\,s^{-1}}$. We also searched for an absorption edge in the energy range 7-10 keV. No statistically significant edge was detected and we place an upper limit of 0.19 (95% confidence) on the optical depth of any absorption edge in the 7-10 keV band.

5. Discussion

The line could arise from the neutron star itself, the accretion disk, or a corona. The high Compton optical depth of the continuum emission likely excludes line production on the neutron star surface as the line would be down-scattered and significantly reduced in intensity. However, line production on the stellar surface cannot be completely excluded if the Comptonizing region is small compared to the stellar radius or comparable to the stellar radius and highly non-uniform.

Production of the line in an accretion disk corona (ADC) should lead to an Fe absorption edge in addition to the emission line. Broadening of a single narrow line via Compton scattering to the width observed would require an optical depth greater than 2.6, in strong contrast to our upper limit of 0.19. Unless the ADC is very highly ionized, suppressing the Fe edge, the low upper limit obtained on the optical depth would argue against significant broadening due to Comptonization. However, the observed broad feature could be a blend of lines originating from an ADC and broadening due to rotation is possible.

Origin of the line in the accretion disk was disregarded in many past studies of broad iron emission features from LMXBs (e.g. White et al. 1985) due to the high ionization expected in the inner parts of the disk. However, the luminosity of 4U 1728-34 is $L_X \sim 0.1 L_{\rm Edd}$ significantly lower than $L_X \sim L_{\rm Edd}$ seen from the brightest LMXBs. Using a thin disk model (Shakura & Sunyaev 1973) in the radiation pressure dominated regime and taking a distance to 4U 1728-34 of 4.2 kpc (van Paradijs 1978) leading to a luminosity $L_X \sim 0.1 L_{\rm Edd}$, a viscosity parameter in the range $\alpha = 0.2 - 0.5$, and assuming illumination from a point source located at the center of the neutron star, we find that the peak ionization, found near a radius of 21 km, is in the range $\xi = 500 - 1200\,{\rm erg\,cm\,s^{-1}}$. This is only a rough estimate since the peak ionization depends on the assumed distance, viscosity, disk model, and source geometry. However, significant iron line flux is expected in this ionization range (Matt, Fabian, & Ross 1996). Our measured line profile is not inconsistent with relativistically broadened line emission from highly ionized iron (Fe XXV to Fe XXVI). To avoid Compton down-scattering similar to that expected to render the line undetectable if emitted from the stellar surface, the Comptonization region must be quite compact. Recent results on energy lags in kHz QPOs in NS-LMXBS favor Comptonization regions with sizes no larger than 10 km (Kaaret et al. 1999). Thus, the accretion disk appears to be a plausible site of origin for the observed line emission.

6. Summary and outlook

We have obtained simultaneous measurements of the x-ray spectrum and the high frequency timing properties of the low-mass x-ray binary 4U 1728-34. We report detection of the highest frequency oscillations, at 1284 ± 6 Hz, yet observed from this source. This is the second highest kHz QPO frequency reported and the highest with a statistical significance above 4σ (van Straaten et al. 2000). Detection of this high frequency may be used to place constraints on the mass-radius relation of the neutron star in 4U 1728-34 (Miller, Lamb, & Psaltis 1998).

We also report detection of a broad emission feature. We suggest that the emission feature may be a relativistically broaden line emitted from the ionized inner accretion disk (Smale et al. 1993). However, the line could, instead, arise from an accretion disk corona, and new observations with much better spectral resolution are called for to constrain the ionization state of the emitting matter and help determine the origin of the line.

To conclude, we offer a few speculations on information that could obtained from future simultaneous timing and spectral observations if the Fe line does arise from the inner accretion disk. Most of the leading models of kHz QPOs in NS-LMXBs identify one kHz QPO frequency with the Keplerian orbital frequency at the inner edge of an accretion disk (Miller, Lamb, & Psaltis 1998, Psaltis & Norman 2000, Stella, Vietri, & Morsink 1999, Titarchuk & Osherovich 1999). A key test of this interpretation would be to find evidence for changes in the disk properties measured via other, i.e. spectral, means correlated with changes in the QPOs. If an Fe line from the inner accretion disk is observable, then the Fe line profile, via relativistic broadening, should provide information on the inner radius of the disk. The QPO frequency is also determined by the inner radius of the disk and the radius and frequency should be related via Kepler's third law, $\nu^2 \propto r^{-3}$. Detection of such a correlation would be a striking confirmation of the interpretation of the kHz QPO frequency as a Keplerian orbital frequency. Furthermore, if this interpretation is correct, simultaneous knowledge of an orbital radius and the associated orbital frequency would lead to a measurement of the compact object mass. Accurate mass determinations are available for binary radio pulsars, but not for accreting neutron stars (van Paradijs 1998) which are of interest because they have undergone significant accretion and, thus, should probe the allowed mass range of neutron stars.

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