XMM-Newton observations of the neutron star X-ray transient KS 1731–260 in quiescence

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ABSTRACT

We report on XMM-Newton observations performed on 2001 September 13–14 of the neutron star X-ray transient KS 1731–260 in quiescence. The source was detected at an unabsorbed 0.5–10 keV flux of only $4 \times 10^{-14}$ erg cm\(^{-2}\) s\(^{-1}\), depending on the model used to fit the data, which for a distance of 7 kpc implies a 0.5–10 keV X-ray luminosity of approximately $2.5 \times 10^{32}$ erg s\(^{-1}\). The September 2001 quiescent flux of KS 1731–260 is lower than that observed during the Chandra observation in March 2001. In the cooling neutron star model for the quiescent X-ray emission of neutron star X-ray transients, this decrease in the quiescent flux implies that the crust of the neutron star in KS 1731–260 cooled down rapidly between the two epochs, indicating that the crust has a high conductivity. Furthermore, enhanced cooling in the neutron star core is also favored by our results.

Subject headings: accretion, accretion disks — stars: individual (KS 1731–260) — X-rays: stars

1. Introduction

X-ray transients are characterized by long episodes (years to decades) of very low X-ray luminosities ($10^{30–34}$ erg s\(^{-1}\)) with occasional short (weeks to months) outbursts during

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which they can be detected at luminosities of $10^{36-39}$ erg s$^{-1}$ (e.g., Chen, Shrader, & Livio 1997). The huge increase in luminosity is thought to be due to a correspondingly large increase in the mass accretion rate onto the compact object in those systems, although the exact mechanisms behind the outbursts are not fully understood (Lasota 2001). Similarly, the exact origin of the quiescent X-ray emission remains elusive. For those systems harboring a neutron star, it has been argued (e.g., Campana et al. 1998b; Brown, Bildsten, & Rutledge 1998) that the observed emission below a few keV originates from the neutron star surface: the neutron star core is heated by the nuclear reactions occurring deep in the crust when the star is accreting and this heat is released as thermal emission during quiescence. The emission above a few keV (as observed in several systems; e.g., Asai et al. 1996, 1998; Campana et al. 1998a, 2000) cannot be explained by this model. Models proposed for this component include residual accretion either onto the neutron star surface or down to its magnetospheric radius, or the radio pulsar mechanism (e.g., Campana et al. 1998b; Campana & Stella 2000).

A sub-class of transients are characterized by very long accretion episodes of years to decades instead of weeks to months. Recently, one of those systems (KS 1731–260) suddenly turned off after having actively accreted for over 12.5 years. A Chandra observation taken a few months after this transition showed the source at a 0.5–10 keV luminosity of $\sim 10^{33}$ erg s$^{-1}$ (Wijnands et al. 2001), assuming a distance of 7 kpc (Muno et al. 2000). If the cooling neutron star model is responsible for the quiescent emission in this system, then it should be in quiescence between outbursts for $>1000$ years, assuming all outbursts are similar to the one observed and standard cooling processes (e.g., modified Urca; Colpi et al. 2001; Ushomirsky & Rutledge 2001) occur in the neutron star core. However, Rutledge et al. (2002) argued that for systems like KS 1731–260, the long accreting episodes will heat the crust to high temperatures and it might take years to decades for the crust to come into thermal equilibrium with the core. Until this happens, the quiescent emission will be dominated by the thermal state of the crust and not that of the core. Rutledge et al. (2002) calculated crust cooling tracks for this source assuming different scenarios of the microphysics involved (the heat conductivity of the crust; standard vs. “enhanced” core cooling).

Burderi et al. (2002) reported on a BeppoSAX observation of KS 1731–260 performed a few weeks before the Chandra observation. They detected KS 1731–260 at a luminosity of at most $\sim 10^{33}$ erg s$^{-1}$. In addition to the cooling neutron star model, they discussed several alternative explanations for the observed quiescent emission (such as residual accretion or the onset of the radio pulsar mechanism). By considering those alternative models, they were able to set an upper limit of $1 - 4 \times 10^9$ Gauss on the magnetic field strength of the neutron star in KS 1731–260. Here we report on XMM-Newton observations of KS 1731–260 taken approximately half a year after the Chandra and BeppoSAX observations. With these XMM-Newton observations we are able to study the time evolution of the quiescent emission.
2. Observation, analysis, and results

We have analyzed XMM-Newton observations of KS 1731–260 performed on 13 September 2001 01:54–09:01 UTC and 13–14 September 2001 22:43–05:58 UTC. All instruments were active; here we only discuss the data as obtained with the three European Photon Imaging Camera (EPIC) instruments (due to the very low flux of the source, it was not detected in the RGS instrument). The two EPIC MOS cameras and the EPIC pn camera operated in full window mode with the thin optical blocking filter. To analyze the data, we used the Science Analysis System (SAS\textsuperscript{6}; version 5.2). We used the calibrated pipeline product data to extract images, light curves, and spectra using the tools available in SAS. Several background flares occurred during our observations, which were filtered out before analyzing the data to minimize the effects of those strong background flares on the quality of the X-ray spectra; we did not use those data during which the count rate exceeded 7 counts s\textsuperscript{−1} for the MOS cameras (using time bins of 10 seconds) and 20 counts s\textsuperscript{−1} for the pn camera (also using 10 seconds time bins). These criteria resulted in a total good time of \(\sim\)23 ksec for the pn camera and \(\sim\)33 ksec for both MOS cameras. No difference in the count rates between the two XMM-Newton observations was observed, and, therefore, we combined the data of both observations to increase our sensitivity.

We combined the data of the three EPIC cameras to create one image of the field of KS 1731–260, representing the most sensitive image of this region so far obtained. In Figure 1, we show both the Chandra/ACIS-S (left) and the XMM-Newton/EPIC (right) images of KS 1731–260. The Chandra image was rebinned by a linear factor of 8 to obtain roughly the same pixel size as that of the XMM-Newton image (3.95\arcsec for the Chandra image vs. 4.35\arcsec for the XMM-Newton image) and both images have been smoothed using a Gaussian function with a width equal to the pixel size of the image. We clearly detected KS 1731–260 together with the nearby star 2MASSI J173412.7–260548 (Fig. 1 right), both of which were also detected during the Chandra observation (Fig. 1 left; Wijnands et al. 2001). To allow for a visual comparison, we used a scaling such that the appearance of this 2MASS star is very similar in both images (below we will show that the flux of this star is consistent with being constant between the two observations). A comparison of the images indicates that KS 1731–260 has decreased in luminosity between the Chandra and XMM-Newton observations. In principle, systematic effects due to the difference in the energy response of the instruments and the different X-ray spectra of the two detected sources might be responsible for this dimming of KS 1731–260 relative to the 2MASS star. However, below we show that the decrease in luminosity as observed for KS 1731–260 is real.

\textsuperscript{6}See http://xmm.vilspa.esa.es/user/sas_top.html
2.1. The source spectra

The spectrum of KS 1731–260 in each EPIC camera was extracted using a circle of 15′′ in radius on the source position. The background spectra were extracted from a circle with a radius of 50′′ close to KS 1731–260 (different background regions resulted in very similar results) which did not contain any other point source (the standard practice of using an annulus around the source position as background could not be used because of the presence of the 2MASS source ∼ 30′′ away from KS 1731–260). The extracted spectra were rebinned using the FTOOLS routine GRPPHA into bins with a minimum of 10 counts per bin. We used the ready-made response matrices provided by the calibration team (available at http://xmm.vilspa.esa.es/ccf/epic/). We fitted the three spectra simultaneously using XSPEC version 11.1 (Arnaud 1996). We used several models to fit the data, and the neutral hydrogen column density $N_H$ was either fixed to $1.1 \times 10^{22}$ cm$^{-2}$ (see, e.g., Barret et al. 1998 or Narita et al. 2001) or left as a free parameter. All single-component models resulted in acceptable fits. Currently, the two models most often used to fit the quiescent spectra of neutron star systems are the blackbody and the neutron star atmosphere models. Therefore, we concentrated on those models, with the neutron star atmosphere model being that described by Zavlin, Pavlov, & Shibanov 1996 (the non-magnetic case). In certain systems, a power-law tail above a few keV was found, and although such power-law component was not required by the data, we fitted the spectra with the above two models including a power-law component with a photon index of 1 or 2 to obtain an upper limit on this component.

The spectral results are listed in Tab. 1 and the pn spectrum is shown in Fig. 2. We have also plotted the spectrum obtained with Chandra (Wijnands et al. 2001), which again suggests that the source was fainter during our XMM-Newton observation than during the Chandra observation. When left free, $N_H$ was consistent with the value previously obtained with other instruments, although for the atmosphere model a slightly higher value was preferred, resulting in a slightly higher unabsorbed flux compared to the fixed $N_H$ case. When $N_H$ was fixed, the atmosphere model measured a similar flux as the blackbody model, $\sim 5 \times 10^{-14}$ erg cm$^{-2}$ s$^{-1}$ (unabsorbed and for 0.5–10 keV). To obtain the errors on the fluxes, we have calculated the $1\sigma$ error contours for the temperature and normalization, fixing $N_H$ at the value in Table 1 in each case, and obtained the fluxes associated with the circumference of the error ellipse. The temperature $kT$ and $N_H$ are strongly correlated in the fits, and when both are free no useful constraints could be obtained on the unabsorbed flux. The best-fit temperature was in all cases $\sim 0.3$ keV for the blackbody fits and $\sim 0.1$ keV for the atmosphere model. In the latter model, the neutron star radius could not be constrained and was fixed to the best fit radius of 15 km (at infinity; the other parameters are not very sensitive to its actual value). When including a power-law component in the fit, it could not be detected significantly and its 0.5–10 keV flux could be constrained to be
less than 25% of that obtained from the blackbody or atmosphere component.

The images and spectra of KS 1731–260 both indicate that the flux decreased between the two observation epochs. To investigate whether the apparent flux decrease is statistically significant, we have fitted the Chandra and XMM-Newton data simultaneously. When all spectral parameters were tied between the two data sets, a blackbody fit is statistically unacceptable, with $\chi^2 = 83$ for 38 degrees of freedom, corresponding to a probability of only $3 \times 10^{-5}$ that the source did not change. We obtained a similar result when we used other models (e.g., atmosphere models) instead of a blackbody. When we did not tie the spectral parameters (except $N_H$ which was assumed to be constant), we obtained acceptable fits. The fit results using a blackbody or an atmosphere model are listed in Table 1. In all cases, the flux difference between the Chandra and XMM-Newton data is significant at a 3 to 4 $\sigma$ level.

Although this shows that the flux of KS 1731–260 decreased, this could conceivably be due to a calibration error in one or both of the instruments. Although this is unlikely (e.g., Ferrando et al. 2002; Weisskopf et al. 2002), we can perform a check on this in the same data set by analyzing the data of both instruments of the 2MASS star assuming that the star has a constant spectrum. To this end, we have extracted the spectra of this source from the Chandra and XMM-Newton data. We fitted all obtained spectra of the 2MASS star simultaneously keeping all spectral parameters tied between both instruments (note that due to low statistics the Chandra data alone did not allow to constrain the source spectrum). Either a blackbody or a power-law spectrum fit the data well, yielding a probability of only 0.12 (blackbody model) or 0.09 (power-law model) that the flux of the 2MASS star changed by the same factor (a factor of 3.5) as we observed for KS 1731–260. Furthermore, a recent cross calibration study between XMM-Newton and Chandra (Snowden 2002) indicates that, for sources with different intrinsic spectra, the measured fluxes of both instruments agree to within 10%. Both these results reinforce the idea that, the flux decrease we observed in KS 1731–260 is real, and not due to calibration problems in any of the two instruments.

In the cooling neutron star model, this flux decrease is due to a temperature decrease. To investigate this, we fitted the two data sets simultaneously with a blackbody model, letting $kT$ float between the two observations, but keeping the same $N_H$ and emitting radius. This resulted in a $kT$ of $0.33^{+0.06}_{-0.05}$ and $0.27 \pm 0.04$ keV for Chandra and XMM-Newton, respectively. The error ellipse of the two temperature parameters (Fig. 3) exclude the line $kT_{\text{Chandra}} = kT_{\text{XMM-Newton}}$, which shows that in the constant-radius blackbody model a systematically lower $kT$ is preferred to fit the XMM-Newton spectrum than the Chandra one, suggesting that the temperature decreased between the two epochs. The resulting fluxes are $11 \pm 2$ (Chandra) and $4.8 \pm 0.8 \times 10^{-14}$ erg cm$^{-2}$ s$^{-1}$ (XMM-Newton). This results in a flux decrease between the two data sets of $6 \pm 2 \times 10^{-14}$ erg cm$^{-2}$ s$^{-1}$, which is significant at the 3$\sigma$ level.
3. Discussion

We have reported on XMM-Newton observations performed on 2001 September 13–14 of the neutron star X-ray transient KS 1731–260 when it was in quiescence. We detected the source at an unabsorbed 0.5–10 keV flux of $\sim 4 \times 10^{-14}$ erg cm$^{-2}$ s$^{-1}$, which for a distance of 7 kpc implies a 0.5–10 keV luminosity of $\sim 2 \times 10^{32}$ erg s$^{-1}$, depending on the model used to fit the data. This luminosity is lower than what has been reported for the source during the Chandra observation performed about half a year earlier (Wijnands et al. 2001; Rutledge et al. 2002). KS 1731–260 is not the only system for which X-ray variability in quiescence has been observed. Several other neutron star systems have also been found to be variable in quiescence by factors of 3 to 5 on time scales of days to years (see Ushomirsky & Rutledge 2001 for a summary of the observed variability).

It is expected that at some level the neutron star in KS 1731–260 should emit X-rays due to the thermal cooling of the neutron star core. Our low X-ray flux provides an upper limit to the thermal flux from the core. If the crust of the neutron star has a higher temperature than the core (Rutledge et al. 2002 argued that the crust should be considerably hotter than the core due to the prolonged accretion episode of KS 1731–260) and/or if additional X-ray production mechanisms are at work in the system (e.g., residual accretion, radio pulsar mechanism), then the thermal flux related to the core will be even lower. Based on the Brown et al. (1998) model and assuming standard core cooling, Wijnands et al. (2001) already calculated that KS 1731–260 had to be in quiescence for over a 1000 years between outbursts in order to emit at the low flux level measured with Chandra (see also Rutledge et al. 2002 or Burderi et al. 2002). However, for the factor of 2 to 4 lower quiescent luminosity we observed with XMM-Newton, this inferred cooling time increases by approximately the same factor. This would make the quiescent intervals of KS 1731–260 extremely long. However, if we assume that enhanced cooling takes place in the neutron star core (e.g., due to enhanced neutrino production), this inferred quiescent interval would decrease considerably, making it more similar to that of the ordinary transients.

In the cooling neutron star model, the variability we observe would have to be explained by assuming that the neutron star surface has cooled between the Chandra and XMM-Newton observations. In the previous section we have presented evidence that the measured temperature decreased, supporting this interpretation. For KS 1731–260, Rutledge et al. (2002) calculated four crust cooling curves assuming different values of the crustal conductivity and the different cooling processes in the core of the neutron star (standard vs. enhanced cooling). A comparison of the observed decrease in luminosity with those cooling curves (see Figure 3 in Rutledge et al. 2002), suggests that our data are only consistent with a highly conductive crust, and likely also enhanced core cooling occurs. For a low heat conductivity
in the crust, the X-ray luminosity of the system should remain constant or even increase slightly, in contrast to what we observed. For a highly conductive crust but only standard core cooling a decrease in luminosity is also predicted, but by an amount that is less than we have observed. However our uncertainties in the actual luminosity decrease are considerable and our data might still be consistent with this possibility. As explained above, the low measured flux of the system by itself already suggests that enhanced core cooling occurs.

In order to calculate the cooling curves, Rutledge et al. (2002) assumed quiescent episodes for KS 1731–260 of 1500 years, which was calculated assuming standard core cooling. However, if enhanced core cooling occurs, the neutron star core can cool more rapidly than assumed and the system could have quiescent episodes of only years to decades. This has to be taken into account in the modeling of the cooling curves. Although the exact implications are unclear, our conclusion that the crust has to be highly conductive to explain the rapid cooling of the crust is unlikely to change. Therefore, within the cooling neutron star model, our new results indicate that the neutron star in KS 1731–260 has a highly conductive crust and enhanced cooling is likely to occur in its core. Colpi et al. (2001) suggested that when the mass of the neutron star exceeds $\sim 1.6 M_\odot$, such enhanced core cooling might occur. A massive neutron star in KS 1731–260 is not unexpected because a significant amount of matter must have been accreted in order for the neutron star to be spinning rapidly. A fast spinning neutron star (with a spin frequency of $\sim 524$ Hz) in KS 1731–260 has been inferred from the burst oscillations detected in this system (Smith, Morgan, & Bradt 1997).

Alternative models explaining the quiescent emission in neutron star X-ray transients have to be considered as well. In models assuming that the emission is due to residual accretion onto the neutron star surface, either directly or via leakage through the magnetospheric barrier, or down to the magnetospheric radius, the detected luminosity decrease can be explained by assuming that the accretion rate has decreased considerably. These alternative models were discussed in detail by Burderi et al. (2002) and because the lower luminosity of KS 1731–260 does not strongly affect their conclusions (an upper limit on the magnetic field strength of the neutron star can be obtained that is a factor $\sim 2$ lower), we will not discuss those models here in detail. Note, that if the luminosity is indeed due to residual accretion, the decrease in accretion rate inferred from our luminosity decrease might cause a change in the X-ray production mechanism due to the fact that the magnetospheric radius might move outside the co-rotation radius or outside the light cylinder (see also Burderi et al. 2002).

With further monitoring observations of KS 1731–260 in quiescence, the quiescent properties of this source and their time evolution will be better constrained. More detailed observations of other quiescent neutron star systems will help to understand how similar they are to KS 1731–260. So far, at least two other systems have been identified with similar prop-
erties: X 1732–304 (Wijnands, Heinke, & Grindlay 2002) and 4U 2129+47 (Wijnands 2002; Nowak, Heinz, & Begelman 2002). Those systems also have very long outburst durations, and from their quiescent properties it has been inferred that they should be in quiescence for hundreds of years if only standard neutron star core cooling occurs. This spurred Wijnands et al. (2002) to suggest that in the standard cooling scenario a correlation between the duration of the outburst episodes and that of the quiescent intervals might be required. However, such a correlation is difficult to understand in accretion disk instability models (Lasota 2001). This could indicate that enhanced cooling takes place in the neutron star cores of those systems (Wijnands et al. 2002). Our results indicating that enhanced cooling may occur in the neutron star core of KS 1731–260 lends further support to this idea.

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Fig. 1.— The *Chandra*/ACIS-S (left; rebinned by a factor of eight) and *XMM-Newton* (right; the MOS1, MOS2, and pn are combined to produce this image) images of KS 1731–260. Both images have been convolved with a Gaussian function with a width equal to the image pixel sizes. The source in the center is KS 1731–260 and the other source to the right bottom is 2MASSI J173412.7–260548. The images were scaled in such a way that the constant source 2MASSI J173412.7–260548 has roughly the same appearance in both images, to show the decrease in luminosity of KS 1731–260.
Fig. 2.— The Chandra/ACIS-S (top spectrum; see also Wijnands et al. 2001) and XMM-Newton/EPIC-pn (bottom) quiescent spectra of KS 1731–260. The solid lines represent the best blackbody fits to the data.
Fig. 3.— The error ellipse of the *Chandra* temperature $kT_{\text{Chandra}}$ versus the *XMM-Newton* temperature $kT_{\text{XMM-Newton}}$. The model used in XSPEC was the bbodyrad model. The plus represent the best fit value. The ellipses are for 1, 2, and 3σ confidence level (for two parameters). The solid line is the line $kT_{\text{Chandra}} = kT_{\text{XMM-Newton}}$. 
Table 1. Spectral results

| Parameter                  | XMM-Newton data | Blackbody | Hydrogen atmosphere |
|----------------------------|-----------------|-----------|---------------------|
| $N_H$ ($10^{22}$ cm$^{-2}$) | $1.1^{+0.6}_{-0.4}$ | 1.1 (fixed) | $1.3^{+0.3}_{-0.4}$ |
| $kT$ (keV)                 | $0.30^{+0.06}_{-0.05}$ | $0.30^{+0.04}_{-0.03}$ | $0.11^{+0.03}_{-0.04}$ |
| $F$                        | $4.8^{+1.0}_{-0.9}$ | $4.8\pm1.0$ | $7.4^{+2.3}_{-1.6}$ |
| $\chi^2$/dof              | 15.7/23         | 15.8/24   | 15.9/23             |

Combined Chandra and XMM-Newton data

| Parameter                  | Blackbody | Hydrogen atmosphere |
|----------------------------|-----------|---------------------|
| $N_H$ ($10^{22}$ cm$^{-2}$) | $0.9^{+0.4}_{-0.3}$ | 1.1 (fixed) | 1.0$\pm0.2$ |
| $kT_{XMM-N}$ (keV)         | $0.31\pm0.05$ | $0.30^{+0.04}_{-0.03}$ | $0.14^{+0.04}_{-0.05}$ |
| $kT_{Chandra}$ (keV)       | $0.29^{+0.06}_{-0.05}$ | $0.27\pm0.03$ | $0.11^{+0.03}_{-0.04}$ |
| $F_{XMM-N}$                | $3.8^{+0.7}_{-0.5}$ | $5\pm1$ | $5.0^{+1.2}_{-0.8}$ |
| $F_{Chandra}$              | $13^{+3}_{-2}$ | $17^{+4}_{-3}$ | $18^{+4}_{-3}$ |
| $\Delta F$                | $9^{+3}_{-2}$ | $12^{+4}_{-3}$ | $13^{+4}_{-3}$ |
| $\chi^2$/dof              | 23.8/36     | 24.6/37   | 23.2/36             |

Note: The error bars represent 90% confidence levels, except for the fluxes for which the errors represent 68% confidence levels. The fluxes are unabsorbed, in the 0.5–10 keV range, and in units of $10^{-14}$ erg cm$^{-2}$ s$^{-1}$. For the blackbody we used the bbodyrad model in XSPEC. For the hydrogen atmosphere model we used the model of Zavlin et al. 1996 (the non-magnetic case) and for this model the neutron star mass was fixed to 1.4 M$_\odot$, its radius at infinity to 15 km, the distance was assumed to be 7 kpc, and the temperature is for an observer at infinity.