THE VARIABLE QUIESCENCE OF CENTAURUS X-4
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ABSTRACT

Centaurus X-4 is one of the best-studied low-mass neutron star transients in quiescence. Thanks to XMM-Newton’s large throughput, Centaurus X-4 was observed at the highest signal-to-noise ratio ever. This allowed us to discern rapid (>100 s), large (45% ± 7% rms in the 10−4 to 1 Hz range) intensity variability, especially at low energies. In order to highlight the cause of this variability, we divided the data into intensity intervals and fit the resulting spectra with the canonical model for neutron star transients in quiescence, i.e., an absorbed power law plus a neutron star atmosphere. The fit is consistent with a variable column density plus variability in (at least) one of the spectral models. Variations in the neutron star atmosphere might suggest that accretion onto the neutron star surface is occurring in quiescence; variations in the power-law tail should support the view of an active millisecond radio pulsar emitting X-rays at the shock between a radio pulsar wind and inflowing matter from the companion star.

Subject headings: accretion, accretion disks — stars: individual (Centaurus X-4) — stars: neutron — X-rays: binaries

1. INTRODUCTION

Many low-mass X-ray binaries (LMXRB) accrete matter at very high rates and therefore shine as bright X-ray sources, but only sporadically. Among these systems are soft X-ray transients (SXRTs) hosting an old neutron star (for a review, see Campana et al. 1998a). These systems alternate periods (weeks to months) of high X-ray luminosity, during which they share the same properties of persistent LMXRBs, with long (1 to a few × 10 yr) intervals of quiescence in which the X-ray luminosity drops by up to 5–6 orders of magnitude.

Cen X-4 is one of the best-studied SXRTs. Bright X-ray outbursts were detected in 1969 and 1979; the source has remained quiescent since. During the 1979 outburst, Cen X-4 reached a peak flux $L_X \sim 4 \times 10^{37}$ ergs s$^{-1}$ (for a distance of $d \sim 1.2$ kpc; Kaluzienski, Holt & Swank 1980). Type I bursts were observed, testifying to the presence of an accreting neutron star. Cen X-4 was observed several times in quiescence (Asai et al. 1996, 1998; Campana et al. 1997, 2000; Rutledge et al. 2001). The spectrum was fitted with a soft thermal component (neutron star atmosphere or blackbody) plus a hard power law with photon index in the 1–2 range. Rutledge et al. (2001) reported that the 0.5–10 keV luminosity decreased by 40% ± 8% in the 5 yr between the ASCA and Chandra observations. This variability can be attributed to the power-law component, since temperature variations in the thermal component are limited to ≤10%. Short-time variability was discovered by Campana et al. (1997) during a ROSAT HRI pointing, with the source flux fading by a factor of $\sim 3$ on a timescale of ≤4 days.

Extensive spectroscopic and photometric measurements of the optical counterpart in quiescence ($V = 18.7$ mag) led to the determination of the orbital period (15.1 hr; Chevalier et al. 1989; McClintock & Remillard 1990; Cowley et al. 1988) and mass function ($\sim 0.2 M_\odot$, implying a neutron star mass between 0.5 and 2.3 $M_\odot$). The optical spectrum shows the characteristics of a K5–7 main-sequence star, contaminated by lines (e.g., H$\alpha$, H$\beta$, and H$\gamma$) and continuum emission probably from an accretion disk (Shahbaz, Naylor, & Charles 1993). The latter was estimated to contribute $\sim 80\%$, $\sim 30\%$, $\sim 25\%$, and $\sim 10\%$ of the quiescent optical flux in the $B$, $V$, $R$, and $I$ bands, respectively. A short wavelength HST FOS spectrum of the quiescent optical counterpart yielded a $1350–2200$ Å luminosity of $6–4 \times 10^{31}$ ergs s$^{-1}$. These results were confirmed by higher quality HST STIS spectra (McClintock & Remillard 2000). In particular, the UV spectrum appears to lie on the extrapolation of the power-law component seen in X rays.

In this paper, we take advantage of an XMM-Newton observation of Cen X-4 to investigate, in much higher detail, its quiescent state. We describe the observation characteristics and data filtering in § 2. In § 3, we discuss spectral and timing results. The interpretation of the data and discussion are presented in § 4. Our conclusions are given in § 5.

2. OBSERVATION AND DATA ANALYSIS

The XMM-Newton Observatory (Jansen et al. 2001) comprises three $\sim 1500$ cm$^2$ effective area X-ray telescopes, each with a European Photon Imaging Camera (EPIC, 0.1–15 keV) at the focus. Two of the EPIC imaging spectrometers use MOS CCDs (Turner et al. 2001), and one uses pn CCDs (Strüder et al. 2001). Reflection Grating Spectrometers (RGS, 0.35–2.5 keV, den Herder et al. 2001) are located behind two of the telescopes.

Cen X-4 was observed on 2001 August 20–21. The EPIC cameras were operated in the prime full window mode with thin filters. We used the data generated by the Pipeline Processing Subsystem in September 2001. The observation is plagued by high background intervals due to soft proton flares. We excluded them using an intensity filter: all events accepted by the intensity filter were considered for analysis.

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FIG. 1.—MOS and pn spectrum of Cen X-4 in the 0.5–10 keV range with the best-fit model (absorbed neutron star atmosphere plus power law) overlaid. The lower panel shows the differences between data and model in terms of $\chi^2$. Dashed lines in the lower panel refer to MOS data.

strength of our source ($\sim 1$ counts s$^{-1}$ in the 0.2–8 keV band of the pn; see below). We verified that the results obtained by using standard thresholds are consistent with the cleaner (but shorter) exposures. We obtained net (original) exposure times of 32 (52), 32 (52), and 24 (40) ks for MOS1, MOS2, and pn, respectively. These represent the deepest observation of a neutron star SXRT ever carried out. RGS spectra were heavily affected by soft proton flares because of the dispersion over the field of view. The optical monitor was not operated.

For the pn, single- and double-pixel events were selected (patterns 0 to 4); for the MOS, events corresponding to patterns from 0 to 12 were selected. Source spectra were extracted from a circular region of 45″ in radius for the two MOS cameras and 40″ for pn camera, corresponding to an encircled energy fraction of $\sim 90\%$. Background spectra have been extracted from nearby circular regions 2′ and 2′5 for the MOS1 and MOS2, respectively. For the pn, we considered two circular regions of 40″ and 60″ in the same CCD of the source. Following the prescriptions of Snowden et al. (2002),$^4$ we extracted the spectra (including the FLAG=0 option) obtaining 9609 counts (0.29 counts s$^{-1}$), 9829 counts (0.30 counts s$^{-1}$), and 28673 counts (1.1 counts s$^{-1}$) from the MOS1, MOS2, and pn in the full band, respectively. Note that pileup was negligible ($< 1\%$).

Response matrices and ancillary region files were generated with the SAS (ver. 5.3.3) tasks rmfgen and arfgen. The spectral analysis was carried out in the 0.5–10 keV energy range for all the instruments using XSPEC (ver. 11.2). All spectral uncertainties are given at the 90% confidence level for one interesting parameter ($\Delta \chi^2 = 2.71$).

3. RESULTS

3.1. Spectral Analysis: I

We first consider the total spectrum. We rebinned the MOS and pn spectra so as to have 25 and 30 counts per spectral channel, respectively. We verified that the background spectra, especially at high energies, are not dominated by residual soft proton flares. In particular, pn and MOS background spectra show the same behavior and decrease by a factor of $\sim 2$ from 2 to 10 keV, as expected for normal conditions (Lumb et al. 2002).

The spectrum cannot be fitted with any single-component model. We then tried the canonical spectrum for SXRT in quiescence (e.g., Campana et al. 1998b; Campana 2001), i.e., an absorbed neutron star hydrogen atmosphere plus a power law (we adopted the absorption model TBABS of Wilms, Allen, & McCray 2000 and the neutron star atmosphere model of Gänsicke, Braje, & Romani 2002). We also included a constant factor to account for the mismatch between the different EPIC instruments (Kirsch 2002).$^5$ This model provides a reduced $\chi^2_{\text{red}} = 1.07$ for 518 degrees of freedom (d.o.f.), corresponding to a null hypothesis probability (n.h.p.) of 12% (see Fig. 1). Neutron star atmosphere models with iron or solar composition or a disk blackbody model provided worse fits with $\chi^2_{\text{red}} > 1.3$. A blackbody model formally provided a better fit to the data, but with a null column density ($< 1.4 \times 10^{20}$ cm$^{-2}$, see Table 1). Taking instead a column density of $9 \times 10^{20}$ cm$^{-2}$ (in line with expectations from optical data), we obtained a worse fit ($\chi^2_{\text{red}} = 1.18$).

The unabsorbed 0.5–10 keV flux of the power-law plus neutron star atmosphere models is $2.3 \times 10^{-12}$ ergs s$^{-1}$ cm$^{-2}$, which, at a distance of 1.2 kpc, translates into a luminosity of $3.9 \times 10^{32}$ ergs s$^{-1}$. In the 0.5–10 keV band, the atmosphere model accounts for 63% of the total luminosity.

3.2. Temporal Analysis

For timing analysis, we considered the entire observation, including high background time intervals. Besides source light curves, we extracted background light curves, which we subtract (including the error on the background rate) from the source light curve. The resulting light curve is clearly not constant (Fig. 2). The importance of the background is in any case minimal, apart from the minimum around 21.5 hr in Figure 2 when the background reached 40% of the Cen X-4 rate.

We extracted light curves in selected energy bands: 0.2–1, 1–2, and 2–8 keV (see Fig. 3). A smaller amplitude of the

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TABLE 1
Spectral Models for the Entire XMM-Newton Observation

| Model            | $N_H$ (10$^{20}$ cm$^{-2}$) | $kT$ (eV) | Photon Index | $\chi^2_{\text{red}}$ (d.o.f.) | n.h.p. (%) |
|------------------|----------------------------|-----------|--------------|-------------------------------|------------|
| Hydrogen         | 8.3 ± 3.5                  | 85 ± 3    | 1.56 ± 0.09  | 1.07 (518)                    | 12.0       |
| Solar            | 11.1 ± 1.5                 | >14       | 3.41 ± 0.08  | 2.88 (518)                    | 0.0        |
| Iron             | 4.5 ± 1.0                  | <273      | 2.79 ± 0.09  | 2.23 (518)                    | 0.0        |
| Disk BB          | 7.3 ± 2.2                  | 219 ± 13  | 1.73 ± 0.13  | 1.31 (518)                    | 0.0        |
| Blackbody        | <1.4                       | 186 ± 5   | 1.64 ± 0.09  | 1.06 (518)                    | 16.1       |

$^4$ See http://xmm.vilspa.esa.es/external/xmm_sw_col/sas_frame.shtml.

$^5$ See http://xmm.vilspa.esa.es/docs/documents/CAL-TN-0018-2-1.pdf.
variability at high energies is apparent. Taking a bin time of 500 s (in order to have a mean of 30 counts per bin in the 2–8 keV light curve), we fitted the light curves with a constant, and we obtained \( \chi^2_{\text{red}} = 13.7, 4.8, 1.6 \) in the three energy bands, respectively. Possible flarelike events can be identified around 14, 16.5, and 22.5 hr in Figure 2. Rise times are about 20 minutes. A diplike feature is also visible around 21.5 hr.

We obtained a power spectrum of the entire observation by using the cleanest pn exposure. The power spectrum shows a strong noise component below \( \sim 0.01 \) Hz (i.e., a timescale longer than \( \sim 100 \) s), consistent with the variability discussed above. The rms variability amounts to 45% \( \pm 7\% \) in the \( 10^{-4} \) to 1 Hz band. The power spectrum can be well fitted with a power law with index \( \Gamma = 1.2 \pm 0.1 \). No significant periodicities or quasi-periodic oscillations are seen. The power-law index of the X-ray power spectrum is consistent with the optical one, which is characterized by an index of \( \sim 1 \) to \( \sim 1.5 \) (Hynes et al. 2002; Zurita, Casares, & Shahbaz 2003).

### 3.3. Spectral Analysis: II

To study possible spectral changes related to the variability, we constructed the color-color diagram made by a soft color (1–2 keV / 0.2–1 keV) versus a hard color (2–8 keV / 1–2 keV; see Fig. 4). Spectral variations are visible in the data. We plot in the same diagram the colors expected for single (absorbed) power-law and neutron star atmosphere spectra for a set of parameters. As expected from the spectral analysis (§ 3.1), these single-component models cannot account for the data. In addition, we plot two lines with different column densities and different fractions of the two-component models. We note that variations in the column density across the observations. Alternatively, a variation in the fraction of the power-law flux to neutron star atmosphere flux can account for the observed variation.

To check these hypotheses, we carry out a more detailed spectral analysis. We concentrate on pn data, since these provide a factor of \( \sim 2 \) more counts than the two MOS cameras together. We divided the data in the pn light curve (1000 s bin) into three different count rates: above \( 1.5 \) counts s\(^{-1}\), between \( 1.0 \) and \( 1.5 \) counts s\(^{-1}\), and below \( 1.0 \) counts s\(^{-1}\). We then fitted the three corresponding spectra in order to search for possible differences. We consider the same absorbed power-law plus neutron star atmosphere model. The same spectrum for the three count rate spectra is clearly not acceptable (\( \chi^2_{\text{red}} = 2.6 \)). Letting the column density vary freely produces an improvement in the fit but not enough to make the fit acceptable (\( \chi^2_{\text{red}} = 1.51 \); the column density is smaller at larger count rates). This shows that the variability cannot be fully ascribed to a column density variation. Better results can be obtained allowing (at least) one of the spectral components to vary together with the column density\(^6\) (Table 2). With an additional parameter, we obtained better results; however, we cannot decide on a statistical basis which of the two fits is better. No

\[ C_{\text{MOS}} = 2 \times 10^{20} \text{ cm}^{-2} \]

\[ C_{\text{pn}} \]

\[ C_{\text{NS}} \]

\[ C_{\text{abs}} \]

\[ C_{\text{neutron}} \]

\[ C_{\text{star}} \]

\[ C_{\text{atmosphere}} \]

\[ C_{\text{power law}} \]

\[ C_{\text{neutron star atmosphere}} \]

\[ C_{\text{X-ray power spectrum}} \]

\[ C_{\text{optical one}} \]

\[ C_{\text{stable}} \]

\[ C_{\text{fits}} \]

\[ C_{\text{better}} \]

\[ C_{\text{remains}} \]

\[ C_{\text{stable}} \]

\[ C_{\text{fits}} \]

\[ C_{\text{better}} \]

\[ C_{\text{remains}} \]
clear correlations are observable. The column density is within the errors for both these new fits. In the case of a variable neutron star atmosphere, the temperature increases with the count rate; in the case of a variable power law, the power-law photon index steepens as the count rate increases.

4. DISCUSSION

The quiescent state of Cen X-4 has been recognized to be variable both on long timescales (~40% in 5 yr; Rutledge et al. 2001) and on shorter timescales (factor of ~3 in a few days; Campana et al. 1997). During this XMM-Newton observation, X-ray variability has been observed (at a level of ~45% rms) on even shorter timescales (down to ~100 s) thanks to the large collecting area. Variability on such a short timescale would have been missed if observed with any previous X-ray satellite.

In the pn light curve, three flarelike events can be identified. X-ray flares have been observed in the transient black hole candidate V404 Cyg also in quiescence (Wagner et al. 1994; Kong et al. 2002). Flare activity has been recently reported also in the optical for a number of transient black holes during quiescence, as well as for Cen X-4 (Zurita et al. 2003; Hynes et al. 2002). Flares occur on timescales of minutes to a few hours, with no dependence on orbital phase, and R-band luminosities are in the range $10^{31}$–$10^{35}$ ergs s$^{-1}$. The mean duration of optical flares in Cen X-4 is 21 minutes. This is similar to what is observed in the X-ray.

Several mechanisms have been proposed for optical flares (Zurita et al. 2003; Hynes et al. 2002). Chromospheric activity, instabilities in the mass transfer rate from the companion, and viscous instabilities in an accretion disk have been ruled out for different reasons (Zurita et al. 2003). Reprocessing of X-ray variations in the outer disk regions has also been considered less likely because of the large ratio between optical and X-ray emission (Zurita et al. 2003). In passing, we note that, in the X-ray light curve, three flare events can be identified (see Fig. 2). The durations and energetics of the first two flares are comparable: 0.9 and 1.2 hr and 1.8 and $4.4 \times 10^{35}$ ergs, respectively. The last flare is much shorter and less energetic (0.1 hr and $0.6 \times 10^{35}$ ergs).

Long-term X-ray variability in the quiescent state of Aquila X-1 has also been reported based on Chandra data. In particular, Rutledge et al. (2002) showed that these variations cannot be caused by variations in the power law only but can be accounted for by a varying temperature of the neutron star atmosphere model. These variations are not monotonic but show first a decrease, then an increase, and finally a decrease in time. This would rule out the deep crustal heating mechanism for SXRTs in quiescence. Campana & Stella (2003) provided a different interpretation of these data (plus additional BeppoSAX observations): a varying column density and power-law component together with a stable neutron star atmosphere model.

This latter model is motivated by the recent discovery of a millisecond radio pulsar PSR J1740–5340 in the globular cluster NGC 6397 (D’Amico et al. 2001; Ferrario et al. 2001). This pulsar shows irregular eclipses in radio, and it is also emitting in X-rays (Grindlay et al. 2001). The X-ray emission is likely powered by the interaction of the relativistic wind of the radio pulsar with matter outflowing from the companion. This shock emission mechanism has also been put forward to explain the X-ray emission of the radio pulsar PSR 1259–63 orbiting a Be companion (Tavani & Arons 1997). This model is not disproved by the data. The power-law photon index is between 1.5 and 2, as one would expect from simple modeling of synchrotron emission. The luminosity increases as the power-law photon index increases, as observed in PSR 1259–63 for $\Gamma < 1.8$.

5. CONCLUSIONS

We observed large (~45%) rms X-ray variability in the quiescent state of Cen X-4. Small spectral variations are observed as well. These can be mainly accounted for by a variation in the column density together with another spectral parameter. Based on the available spectra, we cannot prefer a variation of the power law over a variation in the temperature of the atmosphere component (even if the first is slightly better in terms of reduced $\chi^2$). This variability can be accounted for by accretion onto the neutron star surface (e.g. Rutledge et al. 2002) or by the variable interaction between the pulsar relativistic wind and matter outflowing from the companion in a shock front (e.g., Campana & Stella 2003).

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REFERENCES
Asai, K., Dotani, T., Hoshi, R., Tanaka, Y., Robinson, C. R., & Terada, K. 1998, PASJ, 50, 611
Asai, K., Dotani, T., Mitsuda, K., Hoshi, R., Vaughan, B., Tanaka, Y., & Inoue, H. 1996, PASJ, 48, 257
Campana, S. 2001, in AIP Conf. Proc. 599, X-Ray Astronomy: Stellar Endpoints, AGN, and the Diffuse X-ray Background, eds. N. E. White, G. Malaguti, & G. G. C. Palumbo (New York: AIP), 63
Campana, S., Colpi, M., Mereghetti, S., Stella, L., & Tavani, M. 1998a, A&A Rev., 8, 279
Campana, S., Mereghetti, S., Stella, L., & Colpi, M. 1997, A&A, 324, 941
Campana, S., & Stella, L. 2003, ApJ, 597, 474
Campana, S., Stella, L., Mereghetti, S., Colpi, M., Tavani, M., Ricci, D., Fiume, D. D., & Belloni, T. 1998b, ApJ, 499, L65
Campana, S., Stella, L., Mereghetti, S., & Cremonesi, D. 2000, A&A, 358, 583
Chevalier, C., Ilovaisky, S. A., van Paradijs, J., Pedersen, H., & van der Klis, M. 1989, A&A, 210, 114
Cowley, A. P., Hutchings, J. B., Schmidtke, P. C., Hartwick, F. D. A., Crampton, D., & Thompson, I. B. 1988, AJ, 95, 1231
D’Amico, N., Possenti, A., Manchester, R. N., Sarkissian, J., Lyne, A. G., & Camilo, F. 2001, ApJ, 561, L89
den Herder, J. W., et al. 2001, A&A, 365, L7
Ferrario, F., Possenti, A., D’Amico, N., & Sabbi, E. 2001, ApJ, 561, L93
Gänsicke, B. T., Braje, T. M., & Romani, R. W. 2002, A&A, 386, 1001
Grindlay, J., Heinke, C. O., Edmonds, P. D., Murray, S. S., & Cool, A. M. 2001, ApJ, 563, L53
Hynes, R. I., Zurita, C., Haswell, C. A., Casares, J., Charles, P. A., Pavlenko, E., Shugarov, S., & Lott, D. A. 2002, MNRAS, 330, 1009
Jansen, F., et al. 2001, A&A, 365, L1
Kaluzienski, L. J., Holt, S. S., & Swank, J. H. 1980, ApJ, 241, 779
Kong, A. K. H., McClintock, J. E., Garcia, M. R., Murray, S. S., & Barret, D. 2002, ApJ, 570, 277
Lumb, D. H., Warwick, R. S., Page, M., & De Luca, A. 2002, A&A, 389, 93
McClintock, J. E., & Remillard, R. A. 1990, ApJ, 350, 386
———. 2000, ApJ, 531, 921
———. 2002, ApJ, 577, 346
Shahbaz, T., Naylor, T., & Charles, P. A. 1993, MNRAS, 265, 655
Strüder, L., et al. 2001, A&A, 365, L18
Tavani, M., & Arons, J. 1997, ApJ, 477, 439
Turner, M., et al., 2001, A&A, 365, L27
Wagner, R. M., Starrfield, S. G., Hjellming, R. M., Howell, S. B., & Krezdli, T. J. 1994, ApJ, 429, L25
Wilms, J., Allen, A., & McCray, R. 2000, ApJ, 542, 914
Zurita, C., Casares, J., & Shahbaz, T. 2003, ApJ, 582, 369