The nearby neutron star low-mass X-ray binary, Cen X-4, has been in a quiescent state since its last outburst in 1979. Typically, quiescent emission from these objects consists of thermal emission (presumably from the neutron star surface) with an additional hard power-law tail of unknown nature. Variability has been observed during quiescence in Cen X-4 on both timescales as short as hundreds of seconds and as long as years. However, the nature of this variability is still unknown. Early observations seemed to show it was all due to a variable hard X-ray tail. Here, we present new and archival observations that contradict this. The most recent Suzaku observation of Cen X-4 finds it in a historically low state, a factor of 4.4 fainter than the brightest quiescent observation. As the spectrum during the brightest observation was comprised of approximately 60% from the thermal component and 40% from the power-law component, such a large change cannot be explained by just power-law variability. Spectral fits with a variable thermal component fit the data well, while spectral fits allowing both the column density and the power law to vary do not, leading to the conclusion that the thermal component must be variable. Interestingly, we also find that the thermal fraction remains consistent between all epochs, implying that the thermal and power-law fluxes vary by approximately the same amount. If the emitting area remains unchanged between observations, then the effective surface temperature must change. Alternatively, if the temperature remains constant, then the emitting area must change. The nature of this thermal variability is unclear, but may be explained by variable low-level accretion.

Key words: stars: neutron – X-rays: binaries – X-rays: individual (Cen X-4)

1. INTRODUCTION

Neutron star low-mass X-ray binaries (LMXBs) are often transient. During outbursts they accrete at a significant fraction of the Eddington luminosity, yet these outbursts tend to only last a few months in most cases. Thus, for the majority of the time, these sources are in a quiescent state where the X-ray luminosity is significantly fainter. The X-ray spectra of neutron star LMXBs during quiescence usually consist of two components: a soft thermal component and a harder power-law component (see, e.g., Campana et al. 1998a for a review). The soft component is usually interpreted as thermal emission from the neutron star surface. The neutron star is heated during outbursts as compression by the accreted material causes nuclear reactions to occur deep in the crust. This heat is then radiated thermally during quiescence (Brown et al. 1998). The hard power-law component is less well understood and may be associated with residual accretion or pulsar shock emission (e.g., Campana et al. 1998b; Campagna & Stella 2000; Menou & McClintock 2001).

Accurately measuring neutron star radii is vital for discriminating between the large range of possibilities for the dense matter equation of state (e.g., Lattimer & Prakash 2007). There are a number of potential methods for constraining neutron star radii, for instance, using X-ray bursts (e.g., Özel et al. 2009; Güver et al. 2010), quasi-periodic oscillations (Miller et al. 1998), or relativistic Fe K emission lines (Cackett et al. 2008b). However, one of the most promising methods for measuring a neutron star radius, \( R \), uses the thermal emission from quiescent neutron stars because, as with any blackbody-like emission, \( f \propto R^2/D^2 \) (where \( f \) is the source flux and \( D \) is the distance). While many quiescent neutron stars are too faint for this method to produce constraining radius measurements, modest constraints have been possible for several objects (e.g., Heinke et al. 2003, 2006; Webb & Barret 2007). Future X-ray telescopes, such as the International X-ray Observatory, will allow accurate radius measurements from many quiescent neutron stars in the Galaxy.

Nevertheless, there may be a potential problem. Quiescent emission from neutron stars has been seen to be variable (Campana et al. 1997, 2004; Rutledge et al. 2001, 2002a; Campana & Stella 2003; Cackett et al. 2005). In most cases, this variability comes from observing sources at different epochs and can be explained away by variations in the power law, for instance, due to changes in residual accretion rate (e.g., Cackett et al. 2005). However, in the case of Cen X-4 (Campana et al. 2004), variability was observed during an XMM-Newton observation, and the nature of the variability remains unclear. If it is due to changes in temperature of the thermal component, this poses problems for neutron star radius measurements. A mechanism for any short-timescale temperature change is uncertain, especially under the standard deep crustal heating picture. Thus, this variability has important implications for radius measurements using thermal emission from quiescent neutron stars.

1.1. Variability in Quiescence

Several explanations have been used to describe the X-ray variability of quiescent neutron star LMXBs. In Aql X-1, Rutledge et al. (2002a) found that the temperature of the thermal component varied between observations. Conversely, an analysis of the same data by Campana & Stella (2003) came to an opposing conclusion, suggesting that the variability could be attributed to correlated changes in the column density and the slope of the power law. Moreover, an analysis of two
observations of the neutron star LMXB in the globular cluster NGC 6440 led Cackett et al. (2005) to suggest that it was the power-law component varying in that object.

Probably, the best-studied quiescent neutron star is Cen X-4, and multiple X-ray missions have observed it in quiescence. Cen X-4 is one of the nearest known quiescent neutron star LMXBs ($D = 1.2 \pm 0.3$ kpc; Chevalier et al. 1989). X-ray variability of Cen X-4 in quiescence has been known for about 10 yr (Campana et al. 1997). It has been seen to be variable over timescales of 5 yr, varying by 40% (Rutledge et al. 2001), over a period of 3 days, varying by a factor of ~3 (Campana et al. 1997), and most recently on timescales as short as 100 s with an rms variability of 45% (Campana et al. 2004). The spectrum of Cen X-4 clearly has both a thermal component and a power law (with an index in the range 1–2) present, yet, studies so far have been inconclusive as to whether it is the temperature of the thermal component, the spectral index of the power law, or the strength of the power-law component that is variable.

Rutledge et al. (2001) find a 40% change in the quiescent luminosity of Cen X-4 between ASCA and Chandra observations ~5 yr apart, which they attribute to the power-law component. However, on shorter timescales it is unclear whether this interpretation holds. Campana et al. (2004) performed a detailed analysis of the quiescent spectrum of Cen X-4, finding variability on 100 s timescales throughout an ~50 ks XMM-Newton observation. A color–color analysis was not conclusive as to the source of the variability, thus, they extracted three separate spectra from the observation depending on the count rate. Based on an analysis of the low, medium, and bright count rate spectra, they remained unable to conclusively determine which component led to the variability.

In this paper, we present an analysis of new Suzaku data of Cen X-4, as well as an analysis of two archival Chandra and XMM-Newton observations of this source. From spectral fitting, we show that the thermal component in Cen X-4 must be variable.

### 2. DATA REDUCTION

In Table 1, we detail all the observations analyzed here. Below we discuss the data reduction for each specific telescope.

#### 2.1. ASCA

We use the pipeline produced spectra for the ASCA observation, obtained from HEASARC. There is a second ASCA observation of Cen X-4 taken in 1997 (Asai et al. 1998). However, as noted by Rutledge et al. (2001) this observation is of significantly lower signal-to-noise ratio (S/N) than the first ASCA observation, and therefore adds little extra to our aim of understanding the variability of Cen X-4.

#### 2.2. Chandra Data Reduction

We reprocessed the data following the standard Chandra analysis threads, using CIAO version 4.2. Both observations used the ACIS-S instrument. The psextract tool was used to extract the source and background spectra. For both Chandra observations, we used a circular source region with a 10 pixel radius, and for the background an annulus with inner radius of 15 pixels and outer radius of 45 pixels centered on the source. The response files were created using the mkacisrmf and mkarf tools. The source spectra were binned to a minimum of 20 counts per bin in the energy range 0.3–10 keV to allow the use of $\chi^2$ statistics in spectral fitting.

#### 2.3. XMM-Newton Data Reduction

Data were analyzed using the XMM-Newton Science Analysis Software, version 9.0.0. Calibrated event lists were created from the Observation Data Files using the latest calibration files. The first XMM-Newton observation was performed with the Metal Oxide Semiconductor (MOS) and PN detectors operated in prime full window mode with the thin filters. This first XMM-Newton observation suffered large background flaring throughout the observation. We therefore only extracted spectra from times with low background. For the MOS detectors, we excluded times when the count rate from events $>10$ keV was higher than 0.5 counts s$^{-1}$. For the PN detector, we excluded times when the count rate from events in the range 10–12 keV was higher than 1.0 counts s$^{-1}$. This reduced the net exposure times to 36.7, 36.5, and 23.0 ks for the MOS 1, MOS 2, and PN detectors, respectively. We used a circular source extraction region of radius 45$''$ for MOS detectors and 40$''$ for the PN. For background extraction regions, we used a source-free, nearly 2$'$ circular region for the MOS detectors, and two source-free, nearby circular regions of 40$''$ and 60$''$ for the PN. Net count rates were 0.27, 0.29, and 1.2 counts s$^{-1}$ for the MOS 1, MOS 2, and PN, respectively. All source spectra were binned to a minimum of 20 counts per bin.

The second XMM-Newton observation was performed with the MOS and PN detectors operated in timing mode. This second XMM-Newton observation also suffered from significant background flaring, therefore we filtered the data, excluding times with high background. For the MOS detectors, we excluded times when the count rate from events $>10$ keV was higher than 0.05 counts s$^{-1}$. For the PN detector, we excluded times when the count rate from events in the range 10–12 keV was higher than 0.5 counts s$^{-1}$. The net exposure times were reduced to 64.3, 63.4, and 58.9 ks for the MOS 1, MOS 2, and PN, respectively. The source extraction regions had RAWX values of 306–330, 296–320, and 31–45 for the MOS 1, MOS 2, and PN, respectively. Background extraction regions were taken

### Table 1

| Mission     | ObsID        | Short Name | Start Date  | Exposure Time (ks) | Reference |
|-------------|--------------|------------|-------------|--------------------|-----------|
| ASCA        | 41008100     | ASCA       | 1994 Feb 27 | 39                 | 1, 2, 3, 4 |
| Chandra     | 713          | CXO1       | 2000 Jun 23 | 10                 | 4         |
| XMM-Newton  | 0067750101   | XMM1       | 2001 Aug 20 | 53                 | 5         |
| XMM-Newton  | 0144900101   | XMM2       | 2003 Mar 1  | 78                 | 6         |
| Chandra     | 4576         | CXO2       | 2004 Jun 21 | 10                 | 6         |
| Suzaku      | 403057010    | SUZ        | 2009 Jan 16 | 147                | 6         |

References.

(1) Asai et al. 1996; (2) Asai et al. 1998; (3) Rutledge et al. 1999; (4) Rutledge et al. 2001; (5) Campana et al. 2004; (6) This work.
toward the edge of the exposed part of the detectors, away from the source, and had RAWX values of 260–284, 261–272, and 7–21 for the MOS 1, MOS 2, and PN, respectively. Net count rates were 0.19, 0.19, and 0.86 counts s$^{-1}$ (respectively for MOS 1, MOS 2, and PN). The background rate was higher during this observation than the first, thus significantly higher counts per bin was required to give significant detections in all bins. We binned to a minimum of 150 counts per bin for MOS 1 and MOS 2, and 500 counts per bin for the PN.

2.4. Suzaku Data Reduction

The Suzaku observations were performed with a full window, and with normal clocking modes, with the telescope at the nominal X-ray Imaging Spectrometer (XIS) aim point. The data were analyzed using HEASoft version 6.8, which includes the Suzaku v15 software.

Data reduction for the XIS detectors, which cover the soft X-ray energy band (approximately 0.5–10 keV), follows. The source spectra were extracted for each detector (XIS 0, 1, and 3) using a circular region of radius 250 pixels, centered on the source. The background spectra were extracted from an annulus with inner radius 300 pixels and outer radius 425 pixels, centered on the source. The responses were generated with the xisdfsgen and xissimarfgen tools. We co-added the spectra from the two front-illuminated detectors (XIS 0 and XIS 3) to increase the S/N. We binned the spectra to a minimum of 250 counts per bin in the 0.5–10 keV energy range.

We also extracted a spectrum from the hard X-ray detector PIN camera, which covers the energy range from approximately 10 to 70 keV. The spectrum was extracted using the hxdpinxbp1 tool which also extracts the background spectrum. The net source exposure was 124 ks; however, the source was not detected, and the spectrum is consistent with the background.

3. SPECTRAL ANALYSIS

The spectrum of Cen X-4 has clearly been shown in the past to have both a thermal and a non-thermal component (see Figure 1). We therefore choose to fit the spectra with an absorbed neutron star hydrogen atmosphere plus power-law model. We use the nsatmos model (Heinke et al. 2006) which includes thermal electron conduction and self-irradiation by photons from the compact object. It also assumes a negligible magnetic field (\(<10^9\) G), which is relevant here. Spectral fitting is performed using XSpec v12 (Arnaud 1996) throughout, and all uncertainties quoted are at the 1$\sigma$ level of confidence.

The aim is to investigate the variability of Cen X-4. Through spectral fitting, we test whether the thermal component is variable, or whether changes in the absorbing column and power-law component can explain the variability. We therefore fit the spectra simultaneously, tying several parameters between the spectra and letting others vary freely. We do this in several ways. First, we allow the temperature of the neutron star atmosphere to vary between observations, but hold the emitting radius fixed at 10 km. Second, we hold the temperature tied between the observations (i.e., the temperature is the same for all observations, but this temperature is a free parameter in the fit), but allow the emitting radius to vary. In both cases, the power-law component is left free to vary, and the photoelectric absorption column density (XSpec model phabs) is tied between all observations. Finally, we also test the possibility that there are changes in both the column density and the power law while the thermal component remains unchanged.

4. LIGHT CURVES

In addition to studying the long-term variability of Cen X-4 from epoch to epoch, we also take a look at the variability during the observations newly analyzed here (XMM2, CXO2, and SUZ). We extracted background-subtracted light curves using the same source and background regions as for
the spectral analysis. Given the low count rate, the light curve from the Suzaku observation is noisy and does not show any clear variability. However, the light curves from both XMM2 and CXO2 show some short-term variability. The light curves from XMM2 are shown in Figure 3, and the light curve from CXO2 is shown in Figure 4.

The XMM2 light curves were extracted from the entire data, including the time periods that were excluded from the spectral analysis due to high background flaring. We show the background-subtracted 0.3–10 keV light curves with 250 s binning from all three EPIC detectors as well as the background light curve from the PN. Some of the variability seen in the light curve may be associated with imperfect background subtraction during periods of high background flaring. A clear example of this is at around 20 ks. However, there is a significant flare in the source light curves at around 37 ks that is during a period of low background, thus is clearly associated with source variability.

In order to investigate the nature of this flare, we extracted light curves in the 0.3–2.0 keV range and the 2.0–10 keV range from the PN data and looked at the hardness ratio (2.0–10 keV count rate/0.3–2.0 keV count rate) for any significant changes (see Figure 5). The flare is prominent in the soft light curve, though there is no significant evolution in the hardness ratio during the flare. It is therefore not possible to conclude which component caused the flare.

We perform a simple test for variability in the CXO2 observation by fitting a constant to the light curve. A constant though there is no significant evolution in the hardness ratio curve significantly above the weighted average (see Figure 4), with the early part of the light

### Table 2

| Parameter          | ASCA | CXO1 | XMM1 | XMM2 | CXO2 | SUZ |
|--------------------|------|------|------|------|------|-----|
| N$_{\text{H}}$ (10$^{20}$ cm$^{-2}$) | 4.9 ± 0.2 |
| $kT_E$ (eV)      | 63.3 ± 0.7 | 59.2 ± 0.4 | 66.2 ± 0.2 | 62.0 ± 0.2 | 51.2 ± 0.6 | 48.2 ± 0.6 |
| Power-law index, $\Gamma$ | 1.24 ± 0.17 | 0.97 ± 0.25 | 1.41 ± 0.05 | 1.26 ± 0.08 | 0.78 ± 0.43 | 1.69 ± 0.17 |
| Power-law norm. (10$^{-5}$) | 7.9 ± 1.6 | 3.1 ± 0.9 | 9.4 ± 0.6 | 5.4 ± 0.5 | 1.4 ± 0.7 | 3.7 ± 0.6 |
| Unabs. 0.5–10 keV flux (10$^{-12}$ erg s$^{-1}$ cm$^{-2}$) | 1.86 ± 0.17 | 1.20 ± 0.13 | 2.09 ± 0.06 | 1.48 ± 0.03 | 0.63 ± 0.10 | 0.47 ± 0.03 |
| Unabs. 0.5–10 keV thermal flux (10$^{-12}$ erg s$^{-1}$ cm$^{-2}$) | 1.00 ± 0.09 | 0.71 ± 0.07 | 1.26 ± 0.04 | 0.90 ± 0.02 | 0.33 ± 0.06 | 0.24 ± 0.02 |

Notes. The neutron star atmosphere model “nstatmos” is used. For all observations, the neutron star radius was fixed at 10 km and the mass at 1.4 $M_\odot$. The distance was fixed at 1.2 kpc. $N_{\text{H}}$ was tied between all observations. $kT_E$ is the effective temperature for an observer at infinity, for $R = 10$ km and $M = 1.4 M_\odot$.

The power-law normalization is defined as photons keV$^{-1}$ cm$^{-2}$ s$^{-1}$ at 1 keV.

### Table 3

| Parameter          | ASCA | CXO1 | XMM1 | XMM2 | CXO2 | SUZ |
|--------------------|------|------|------|------|------|-----|
| N$_{\text{H}}$ (10$^{20}$ cm$^{-2}$) | 5.6 ± 0.6 |
| $kT_E$ (eV)      | 79.3 ± 2.5 |
| Radius (km)       | 10.8 ± 0.6 | 9.7 ± 0.6 | 11.7 ± 0.8 | 10.5 ± 0.5 | 7.8 ± 0.4 | 7.2 ± 0.3 |
| Power-law index, $\Gamma$ | 1.29 ± 0.11 | 0.85 ± 0.14 | 1.51 ± 0.04 | 1.22 ± 0.05 | 0.31 ± 0.16 | 1.53 ± 0.10 |
| Power-law norm. (10$^{-5}$) | 8.5 ± 1.7 | 2.6 ± 0.8 | 11.1 ± 0.8 | 5.1 ± 0.5 | 0.8 ± 0.5 | 3.0 ± 0.6 |
| Unabs. 0.5–10 keV flux (10$^{-12}$ erg s$^{-1}$ cm$^{-2}$) | 1.88 ± 0.15 | 1.24 ± 0.12 | 2.13 ± 0.05 | 1.51 ± 0.05 | 0.72 ± 0.10 | 0.48 ± 0.04 |
| Unabs. 0.5–10 keV thermal flux (10$^{-12}$ erg s$^{-1}$ cm$^{-2}$) | 1.01 ± 0.08 | 0.74 ± 0.07 | 1.27 ± 0.03 | 0.94 ± 0.03 | 0.35 ± 0.05 | 0.25 ± 0.02 |

Notes. The neutron star atmosphere model “nstatmos” is used. For all observations, the mass was fixed at 1.4 $M_\odot$. The distance was fixed at 1.2 kpc. Both $N_{\text{H}}$ and $kT_E$ were tied between all observations. Note that here we give the unshifted $kT_E$ as the emitting radius (and thus the redshift) is allowed to be different at each epoch. The power-law normalization is defined as photons keV$^{-1}$ cm$^{-2}$ s$^{-1}$ at 1 keV.
are for varying temperature and fixed radius. What is clear from the spectral fits is that the thermal component has to have varied between these two epochs. Given that the power-law accounts for approximately 40% of the 0.5–10 keV flux in XMM1, a factor of 4.4 change in flux cannot be achieved through a variable power-law alone. The spectral fits allowing both the power law and column density to vary also do not fit the data well, leading to a significantly worse fit ($\chi^2_{\nu} = 1.47, \nu = 1165$) than when allowing the thermal component to be variable.

A spectral fit with the temperature tied between all observations and the radius fixed at 10 km is statistically not acceptable ($\chi^2_{\nu} = 1.91, \nu = 1171$). All of the brightest observations have very soft power-law indices ($\sim 3$), and poor fits above 3 keV, as the power-law component tries to fit the majority of the thermal component. We also tried fitting with the radius as a free parameter, though having its value be the same for all observations, however this does not significantly improve the fit ($\chi^2_{\nu} = 1.90, \nu = 1170$). Thus, the spectral fits demonstrate that the thermal component must vary between epochs, and the variability cannot be attributed to changes in the power-law index, normalization, and/or the absorption.

Figure 2 shows the long-term variability of Cen X-4. The top three panels in this figure show the variability of the (a) unabsorbed 0.5–10 keV flux, (b) effective temperature, and (c) fraction of flux in the thermal component from the spectral fits where the temperature is variable between epochs and the radius is fixed. Both the changes in flux and temperature follow the same overall pattern. In fact, it can be seen that the thermal fraction remains consistent between epochs, implying that the flux from the thermal and power-law components is varying by approximately the same amount. The bottom panel, (d), shows how the radius changes in the case where the temperature is tied between each epoch in the spectral fits. It demonstrates that in this model, significant changes in the radius are required to account for the spectral changes. Therefore, to achieve the observed flux variability, either the temperature of the thermal component or the emitting radius must vary between epochs. We cannot rule out that both the temperature and the radius change.

For the sake of completeness, we also note several previous quiescent observations not studied here. *Einstein* and EXOSAT observations were performed in 1980 and 1986, respectively (van Paradijs et al. 1987), though their flux measurements are not precise enough to be constraining here (see table 2 from Rutledge et al. 2001, which concisely summarizes these observations). ROSAT/High Resolution Imager observed Cen X-4 in 1995 (Campana et al. 1997), however, given that this was not a spectral instrument no tight flux constraint is obtained. As noted earlier, there was a second ASCA observation of Cen X-4 in quiescence (Asai et al. 1998), which was unfortunately of low quality. This observation was performed on 1997 February 4–5. The analysis by Asai et al. (1998) led to a rather poorly constrained unabsorbed 0.5–10 keV flux of $1.75^{+1.75}_{-1.17} \times 10^{-12}$ erg s$^{-1}$ cm$^{-2}$, consistent with all but our faintest observation. Finally, a BeppoSAX observation was performed on 1999 February 9 (Campana et al. 2000), and this was found to be consistent with the first *Chandra* observation (Rutledge et al. 2001).

6. DISCUSSION

The two known outbursts from the neutron star LMXB Cen X-4 were in 1969 and 1979, and the source has been in quiescence ever since (it has not been detected in outburst by any mission or all-sky monitor). Our spectral analysis of six observations during quiescence covers a period of over 15 yr and shows variability of a factor 4.4 between the brightest and faintest states. In all observations, both a thermal and a power-law component are present in the spectrum. The amplitude of the observed variability requires that the power-law alone

![Figure 2](image-url)
cannot account for the variability, as the power-law component contributes only about 40% of the flux during the brightest state. Our spectral fitting demonstrates that the thermal component must vary with either the temperature and/or the radius of the thermal component changing between epochs. Allowing both the power-law component and the column density to vary (while the thermal component remains constant) does not fit the data well.

In addition to the long-term epoch to epoch variability, we have observed short-term variability on timescales of the order of a few hundred seconds in the light curves from two of the newly analyzed data sets (XMM2 and CXO2). Such short-term variability has previously been observed in Cen X-4 (Campana et al. 2004), though the nature (whether thermal or power law) was inconclusive. Given that the source was fainter during these two new observations than during the study by Campana et al. (2004), we again are unable to determine the cause of this short-term variability.

There are several methods by which the temperature of the neutron star surface may change on timescales of years, which we now discuss in turn. First, once a source returns to quiescence, the crust may cool (e.g., Rutledge et al. 2002b). In the case where the outburst is particularly long (i.e., lasting several years rather than several weeks to months), the crust can...
be heated significantly out of thermal equilibrium with the rest of the star. Therefore, once accretion reduces to quiescent levels, the crust will thermally relax. Such crustal cooling has been observed in four sources so far. This cooling was first observed in KS 1731−260 and then seen in MXB 1659−29, with both sources returning to quiescence in 2001 (Wijnands et al. 2001, 2003). Since then, monitoring with Chandra and XMM-Newton has shown both sources to cool rapidly (Wijnands et al. 2002, 2004; Cackett et al. 2006). The cooling curve of MXB 1659−29 covers 6.6 yr and is well described by an exponential decay to a constant level, with an e-folding timescale of 465 ± 25 days (Cackett et al. 2006, 2008a). While the cooling curve of KS 1731−260 can also be described by exponential cooling to a constant, with a similar e-folding time (Cackett et al. 2006), the most recent observation suggests that cooling is continuing following a power-law decay (Cackett et al. 2010).

In the last couple of years, two additional sources with long outbursts have also gone into quiescence (Degenaar et al. 2009; Fridriksson et al. 2010). The neutron star transient EXO 0748−676 was in outburst before returning to quiescence. Chandra and Swift observations covering the first five months after the source transitioned to quiescence show an initially slow decrease in temperature (Degenaar et al. 2009), with further observations ongoing. Finally, once the transient XTE J1701−462 returned to quiescence it displayed rapid cooling (Fridriksson et al. 2010). However, the cooling curve observed is complicated by a temporary increase in temperature about 220 days into quiescence. After this increase the cooling continued on the same track as before the increase—an exponential decay to a constant, with an e-folding time of about 120 days. Fridriksson et al. (2010) suggest that the apparent increase in temperature could be caused by an increased level of accretion.

The long-term quiescent light curve for Cen X-4 (Figure 2) may show an overall decrease suggestive of cooling, but with several increased points, as observed in XTE J1701−462. Clearly, though, the sampling rate is extremely infrequent and there are only a small number of points. However, the timescale of any apparent decrease is significantly longer than the e-folding timescales for the crustal cooling sources discussed above. The variability we observe from Cen X-4 is from 15 to 30 yr after the 1979 outburst, and thus the crust should have cooled back into thermal equilibrium with the core at this point if it has a similar structure to the other sources. It therefore seems unlikely that crustal cooling contributes significantly to the variability observed. Note that the neutron star core will not cool appreciably over the timescales observed here (e.g., Yakovlev & Pethick 2004) and thus will not contribute to any variability.

Continued low-level accretion onto the neutron star surface can also change the thermal properties of the star. The thermal quiescent flux is sensitive to both the amount of H/He remaining on the surface after an outburst and to the composition of ashes from previous H/He burning (Brown et al. 2002). Continued low-level accretion will change the surface composition by adding an insulating layer of ashes from H/He burning. This therefore changes the effective surface temperature and can occur on timescales of >10 yr at the luminosity of Cen X-4. However, this effect should lead to an increase in temperature over time. Specific calculations for Cen X-4 by Brown et al. (2002) suggest only a 20% increase in brightness over 30 yr due to this effect. Here, we see variations greater than 20% and variability that is not just a simple increase, suggesting that an increase in the depth of the H/He layer cannot explain the observed variability in Cen X-4.

Another process by which the thermal properties of a quiescent neutron star may vary is diffusive nuclear burning (Chang & Bildsten 2003). In this process, hydrogen diffuses to deeper layers in the crust where it can fuse. This would lead to a drop in flux as hydrogen is consumed and the hydrogen abundance in the photosphere decreases. This process is only expected to lead to changes on timescales >10 yr. For Cen X-4, Chang & Bildsten (2003) specifically predict that 20 yr after the outburst the flux will vary by only 3% over a 10 yr timescale, and that roughly 100 yr after the outburst the flux will drop by 12% over a 20 yr period. Consequently, it is hard to explain the observed variability by this process, given that we see variability of much greater amplitude than this as well as more than just a simple flux decline.

The above explanations are also disfavored because the thermal fraction is constant while the luminosity varies. However, one other possibility is that variable residual accretion is responsible for the observed behavior. If low-level accretion onto the neutron star surface is causing the power-law component in the spectrum, then an increase in this accretion rate would increase the power law, which could in turn lead to an increase in the observed neutron star temperature. In fact, residual accretion is known to be able to produce a thermal spectral shape (Zampieri et al. 1995). One striking finding is that while the total luminosity varies by a factor of over four, the ratio of thermal to power-law flux remains approximately constant (Figure 2, panel (c)). This appears to indicate that the thermal and power-law components are linked together, thus any mode for residual accretion would need to produce both components and in a way that their ratio remains constant. This may be able to provide constraints on models of accretion flows at low mass-transfer rates.

In summary, the crustal cooling, H/He ashes, and diffusive nuclear burning processes all seem unlikely to drive the thermal variability observed, and the most likely scenario appears to be one where variable low-level accretion causes both the thermal and non-thermal variability. More frequent monitoring of Cen X-4 will lead to a better understanding of both the amplitude and timescales of the variability. Finally, this thermal variability may pose a problem for measuring neutron star radii from modeling quiescent emission given that it is not clear whether the variability is caused by the emitting radius, the temperature, or both. If the variability is due to low-level accretion, then avoiding sources with a significant power-law component would be beneficial.

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