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Variability in the Quiescent State of Neutron Star Transients

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Abstract. Variability studies represent a powerful tool to assess the emission mechanism(s) at work in the quiescent state of transient low-mass X-ray binaries. Here we report on *Chandra* and XMM-*Newton* observations of two well-known transient sources: Aql X-1 and Cen X-4. Long- and short-term variability is observed. This variability can be easily interpreted as coming from an active millisecond radio pulsar emitting X-rays at the shock between a radio pulsar wind and inflowing matter from the companion star.

1. Introduction

Many Low-Mass X-ray Binaries (LMXBs) accrete matter at very high rates, and therefore shine as bright X-ray sources only sporadically. Among these systems are Soft X-ray Transients (SXTs) hosting an old neutron star (for a review see Campana et al. 1998). These systems alternate periods (weeks to months) of high X-ray luminosity, during which they share the same properties of persistent LMXBs, to long ($\sim 1-10\,$yr) intervals of quiescence in which the X-ray luminosity drops by up to 5–6 orders of magnitude.

Short-term variability is a powerful tool for the study of the emission mechanism(s) responsible for the SXTs quiescent emission. A factor of 3 variability over timescales of days (Campana et al. 1997) and of 40% over 4.5 yr (Rutledge et al. 2001) have been reported in Cen X-4. Several other transient neutron-star systems have also been found to be variable in quiescence by factors of 3–5 (e.g., Rutledge et al. 2000) but data have been collected over several years and with different instruments. Here we report on recent results obtained on two of the best studied sources of this class.

2. Aql X-1

Rutledge et al. (2002), analysing *Chandra* data of the Aql X-1 quiescent phase after the November 2000 outburst, found a variable flux and X-ray spectrum. They interpreted these variations in terms of variations of the neutron-star effective temperature, which changed from 130^{+3}_{-5} eV, down to 113^{+3}_{-4} eV, and finally increased to 118^{+9}_{-4} eV, suggesting that low-level accretion is continuing in quiescence.

The *Chandra* data on Aql X-1 are the first that show a clear luminosity variation and, more importantly, an increase of the temperature during quiescence. Campana & Stella (2003) used the same *Chandra* data plus an unpublished long BeppoSAX observation carried out in the same period to probe a different spectral model. Deep crustal heating (Brown et al. 1998; Colpi et al. 2001) has been proposed as a physically sound mechanism powering the soft component of the quiescent spectra of SXTs. Several mechanisms have also been proposed to explain the hard tail component often observed in quiescent SXTs. One of them, physically motivated by the recent observations of the millisecond radio pulsar (MSP) PSR J1740−5340 (D'Amico et al. 2001; Grindlay et al. 2001), relies on the shock emission between the relativistic MSP wind and matter outflowing from the companion (Tavani & Arons 1997; Campana et al. 1998). These two components are not exclusive.

Within this physical scenario, we fit the spectra fixing the soft component for all the observations and leave free to vary the hard component *and* the column density (that changes by a factor of ~ 5). This model is consistent with the entire dataset ($\chi^2_{\rm red} = 1.00$, for 109 d.o.f. and with a null hypothesis probability of 49.0%). Fitting the same dataset with the best-fit model by Rutledge et al. (2002) with the addition of the BeppoSAX data, we obtain a slightly worse fit ($\chi^2_{\rm red} = 1.17$, for 113 d.o.f. and with a null hypothesis probability of 11.1%). We conclude that the scenario proposed is (at least) equally consistent with the data, meaning that a shock-emission scenario can account for the spectral variability observed in Aql X-1. We also note that Rutledge et al. (2002) found 32% (rms) variability in the latest *Chandra* observation. In their case the power-law component contributed only 12% of the flux. From our fit, the power-law component contributes 38% of the total flux, so it can in principle account for all of the short-term variability.

Despite the low number of points, spectral parameters derived for the power-law index show some correlation with the column density (interpreted as a measure of the variable mass around the system, over a fixed interstellar amount) as well as with the power-law flux. This correlation might be expected in the shock-emission scenario (Tavani & Arons 1997). What is now expected is the large value of the power-law index in the latest observations. This might then provide an indication of a different regime in the system, possibly underlying a larger inverse Compton cooling.

3. Cen X-4

Thanks to XMM-*Newton*'s large throughput, Cen X-4 was observed at the highest signal-to-noise ratio ever. This allowed us to reveal rapid (> 100 s), large (45 ± 7% rms in the $10^{-4} - 1$ Hz range) intensity variability, especially at low energies (Campana et al. 2004). The power spectrum can be well fit with a power law of index -1.2 ± 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 ~ -1, -1.5 (Hynes et al. 2002; Zurita et al. 2003).

In the pn light curve three flare-like events can be identified. Flare activity has been 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). In the optical flares occur on timescales of minutes to a few hours, with no dependence on orbital phase. R-band luminosities are in the range $10^{31} - 10^{33}$ erg. The mean duration of optical flares in Cen X-4 is 21 min. This is similar to what is observed in X-rays.

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. Small spectral variations are observed. 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 versus a variation in the temperature of the atmosphere component (even if the first is slightly better in terms of reduced χ^2).

4. Conclusions

Variations in the temperature of the neutron star atmosphere might suggest that accretion onto the neutron star surface is occurring in quiescence; variations in the power-law tail (photon index) together with variations in the column density 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. We tested both models with the latest data on Aql X-1 (long-term variability with *Chandra*) and Cen X-4 (short-term variability with XMM-*Newton*). Either model can explain equally well the observational data.

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