Final Technical Report
NASA GRANT: NAG5-11419
Title: Quiescent Emission from Transient Type-I X-ray Bursters
Principal Investigator: Robert E. Rutledge

The purpose of the funded activity was to analyze and interpret data obtained with the European Space Agency X-ray Multiple Mission (XMM) observatory, of two transiently accreting type-I X-ray bursters observed in the field, Cen X-4 and Aql X-1. Both observations were accepted as class-A for AO-1.

The main goal of the analysis is to measure the X-ray spectrum of the neutron stars in these systems, and interpret them as H atmosphere neutron stars, and measure their radii. Secondarily, the behavior of the systems were expected to adhere to the predicted properties of a quiescent neutron star system – specifically, to have a constant intensity.

The Cen X-4 observation was completed successfully 21 Aug 2001. The observation was 53000 seconds of realtime, with approximately 38ksec of livetime in the EPIC/pn instrumentation, which was the primary instruments for this observations. However, the background countrate due to particles in the instrumentation were highly variable – changing by a factor of 10 during the process of the observation, on timescales of $\sim$100 sec (see Fig. 1). An inquiry to the telescope operations regarding re-observation of Cen X-4, due to unacceptably high background variability, found that such could not be accommodated.

To analyze these data for variability, we developed a Fourier-analysis-based technique, where we measure the Fourier components in 6 adjacent spatial (background) regions, and interpolate to a predicted Fourier spectrum in the source region. We subtract this background Fourier spectrum, and are left with the source Fourier variability spectrum (i.e., the power density spectrum).

This analysis demonstrated that the X-ray source exhibited significant variability during the observation – approximately 44$\pm$2% root-mean-square variability on timescales between 0.1-10,000 sec in the 0.2-2.0 keV photon energy range. In the 2-8 keV range, the 90% confidence limit on variability is $<$42% rms. Variability of this strength on this timescale in the thermal component, which dominates the low-photon energy range, is far in excess of that expected from a quiescent, non-accreting neutron star; quiescent neutron stars should be $\ll$1% variable on these timescales. The X-ray luminosity of the source ($\sim 7 \times 10^{32}$ergcm^{-2}s^{-1}) was close, but slightly above, that measured during previous observations in quiescence. The most obvious conclusion to draw from this variability is that accretion onto the neutron star surface is active in Cen X-4 during this observation.

While in the process of performing this variability analysis, we discovered a "phase lag" between the high energy photons and the low energy photons, which was timescale dependent (it become significant at frequencies $>$0.1 Hz (i.e, on timescale shorter than 10 seconds). If this phase-lag were intrinsic to the source, it would imply a correlation between variations in the high-energy photons and

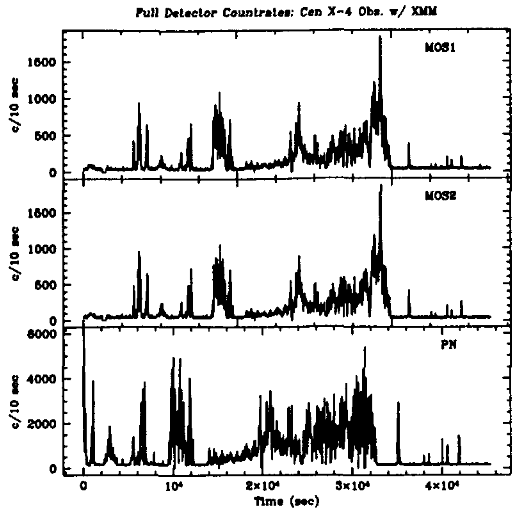

Figure 1: Full detector countrates (in counts/10 sec bin) for the MOS-1 (top panel) MOS-2 (middle panel) and PN detectors (bottom panel). Extremely large excursions from a constant are observed, indicating large background flares during the observation.

the low-energy photons. Such a phase-lag is therefore physically important, as it would unequivocally tie the power-law spectral component with emission in thermal component – that is, directly to the surface emission of the neutron star. However, in calibrating this effect, we performed an identical analysis from a supernovae remnant with a similar countrate to Cen X-4 – 1ES0102-72 (obs. 0135720601). We show this phase-delay spectrum in Fig. 2. The phase-delay in the supernovae remnant – which should exhibit no intensity variability, and therefore no phase delay – is identical in sign and magnitude to that measured in Cen X-4. We can only conclude that this is due to an instrumental effect, which may be comparable to a electronics dead-time effect. It is therefore not intrinsic to Cen X-4. This apparent dead-time effect is presently undocumented with the instrumental effects of XMM/pn.

X-ray CCD-resolved spectroscopy revealed an integrated spectrum similar to that observed (with significantly less signal-to-noise) from Cen X-4 with Chandra – an absorbed thermal spectrum dominating below 2 keV, with an inverted power-law component above 2 keV. However, given the intensity variability during the observation, the behavior of the spectrum as a function of intensity is of great interest. We subsequently divided the spectrum into four intensity ranges, based on the instantaneous countrate of the source (in practice, the countrate averaged over 100 seconds).

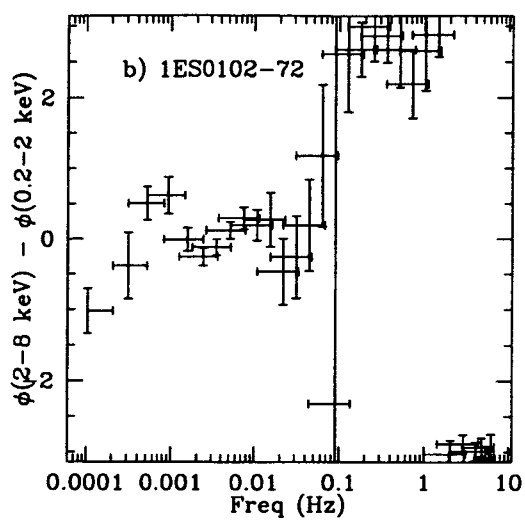

Figure 2: Phase delay spectrum for SNR 1ES0102-72 (countrate ~5 counts/sec) taken with EPIC/pn. An anti-correlation is observed at frequencies >0.1 Hz. As no phase-delay is expected from a supernovae remnant, this implies the phase-delay is due to an instrumental effect, the origin of which we do not know, but may be an electronics deadtime effect.

Simple examination of the spectrum reveals that all the intensity variability is in the thermal portion of the spectrum (<3 keV), with no evidence of variability in the power-law dominated portion of the spectrum. Comparison of the highest- and lowest-intensity spectra, using spectral fitting techniques, and a standard quiescent neutron star model (H atmosphere + power-law) showed that the different between these two spectra could not be explained by permitting only the power-law normalization to vary; however, the difference can be explained if both the power-law normalization and slope varies (the photon power-law slope changes from 1.3 to 2.6).

In addition, the differences between the two spectra can be explained by the power-law component remaining the same and the neutron star effective radius remaining the same, while the temperature of the thermal component varies. However, the spectrum is inconsistent with a constant power-law component and a constant neutron star effective temperature, but with a variable neutron star radius.

By far, this observation of Cen X-4 is the highest S/N observation of a quiescent neutron star, to date, and will likely remain so for a long time. The short-timescale variability appears to be due to active accretion in the system. The spectral analysis, however, is inconclusive. If spherically-symmetric active accretion is taking place onto the NS, then the spectrum is as expected, with an increasing/decreasing temperature as a function of intensity; and the power-law component (the origin of which remains unknown) is constant. Alternatively, accretion variability may be powering power-law component variability, with the thermal component remaining constant. A conclusive observation must be made in the future.

These analysis results are written up, although the interpretation has not yet been completed. The intention of this study was to join this observation with the observation of the second source – Aql X-1 – so that stronger conclusions based on observations of both sources could be made. However, due to programmatic considerations unforseen by the telescope planners, the observation of Aql X-1 was not performed until July, 2004 – three years after the AO period for which it was accepted. We are in the process now of analyzing the Aql X-1 data.

An aspect which greatly strengthens the utility of the late Aql X-1 observations, however, is that in the interim, we have collected 11 individual observations of the same system with the Chandra X-ray Observatory. This provides a large database of observations to inter-compare, to search for variability and detect X-ray spectral evolution between them. We are in the process of performing this work now, supported separately; when the analysis is complete, it will be submitted in toto to the Astrophysical Journal.

XMM-Newton Guest Observer Program Summary of Research

Budget Principal Investigator Dr. Robert E. Rutledge	Proposal Number: 6775 Grant Number: NAG5-11419
Name and Address of Institution California Institute of Technology 1200 California Blvd. Pasadena, CA 91121	[redacted] Award Period: 01/01/02-12/31/03 Current Date: Sept 2 2004 Telephone: (626) 395-6809 Fax: (626) 449-8676
Proposal Title Quiescent Emission from Transient Type I X-Ray Bursters	E-mail Address rutledge@tapir.caltech.edu Congressional District California 27

Cite title(s) and publication date(s) for publication of project results:
Astrophysical Journal, in preparation

Objectives of the research and the results obtained (attach additional pages if needed).
See Attached.

Signature of the Budget PI Robert E. Rutledge

Date Sept 2, 2004