Dartmouth

An investigation of luminous X-ray pulsars: Exploring accretion onto the magnetized neutron star LMC X-4

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1. Neutron stars - a highly magnetic laboratory

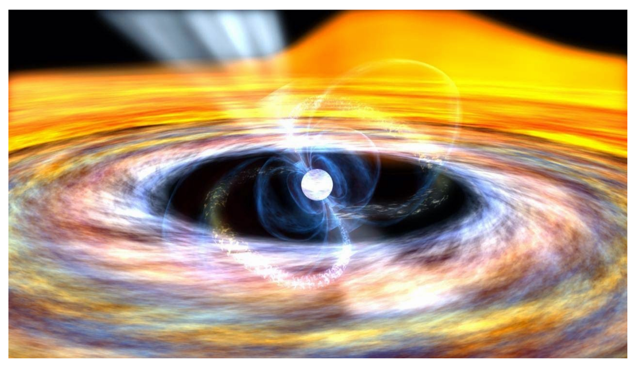

Figure 1: An artist's rendition of a truncated accretion disk around a magnetized neutron star. Image credit: NASA/GSFC/Dana Berry.

Neutron stars, with densities similar to that of the atomic nucleus and magnetic fields as high as 10^{13} G, provide a unique laboratory in which to examine how matter behaves under extreme conditions (e.g. Chamel et al. 2013, Pons et al. 2013). X-ray pulsars, rapidly rotating neutron stars that form in binary stellar systems and accrete matter from a companion, provide an opportunity to examine magnetic accretion mechanisms. At the edge of the pulsar's magnetosphere, the pressure from the magnetic field can exceed the ram pressure of the disk, causing the accretion to become dominated by magnetic forces, as seen in Figure 1 (e.g. King et al. 2016). Simulations of magnetic accretion indicate that the inner accretion disk can become warped by magnetic forces (Romanova et al. 2004).

2. A warped inner disk leads to hard and soft X-ray emission

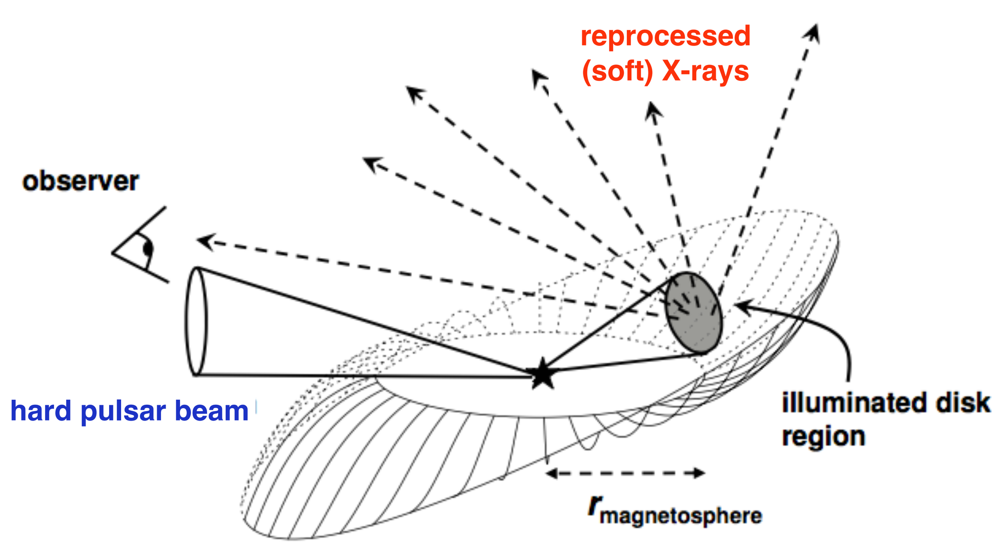

Figure 2: Model of a warped inner accretion disk, where the observer sees both hard emission from the pulsar beam and reprocessed photons from the disk. Model from Hickox & Vrtilek (2005).

LMC X-4 is a high mass X-ray binary that displays consistent luminosity variability, which indicates that a warped inner accretion disk partially obscures the pulsar during its precession. As the pulsar's hard X-ray beam sweeps across the inner accretion disk (Figure 2), the disk reprocesses the radiation and emits soft X-ray photons. (Hickox et al. 2004).

We hope to **capture a complete precession of the disk** and examine emission from the pulsar and the disk simultaneously in order **to reconstruct the kinematics and geometry of the inner accretion disk in LMC X-4.**

3. Capturing the spectrum with *XMM-Newton* and *NuSTAR*

Both high and low energy X-ray sensitivity are needed to fully observe radiation from both the disk and the pulsar. *NuSTAR* is capable of detecting the hard emission from the pulsar (Harrison et al. 2013), while *XMM-Newton* can observe the reprocessed X-ray photons. Four joint observations of LMC X-4 were conducted with *XMM-Newton* and *NuSTAR* between 30 October 2015 and 27 November 2015. These observations, see Figure 3, fall in a single superorbital cycle, and will allow us to track the precession of the accretion disk relative to the pulsar.

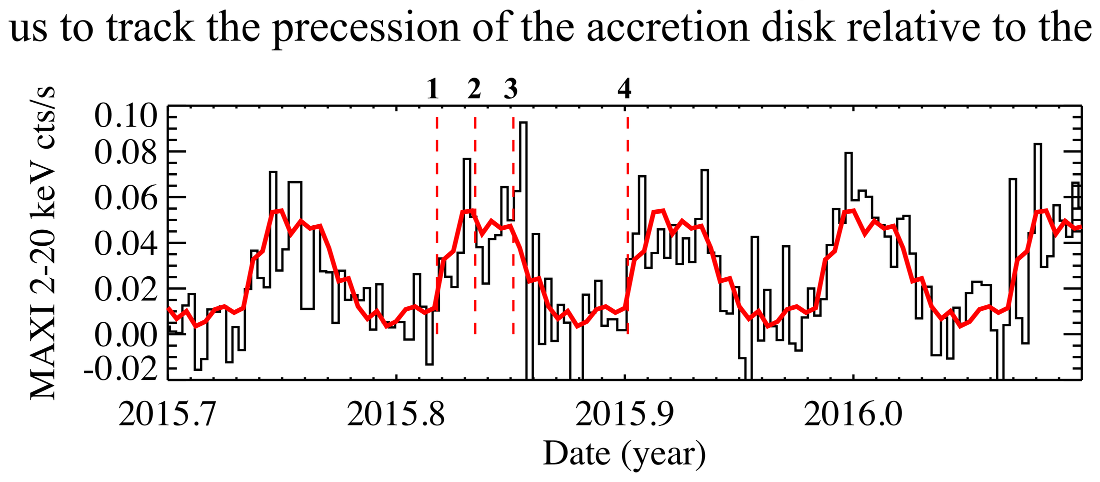

Figure 3: One day averaged light curve corresponding to 1.5 years of observation of LMC X-4 with MAXI (Matsuoka et al. 2009). The red line is the best fit to the 30.49 day superorbital period. Vertical dashed lines mark the times of four joint *XMM* and *NuSTAR* observations.

4. From raw data to results

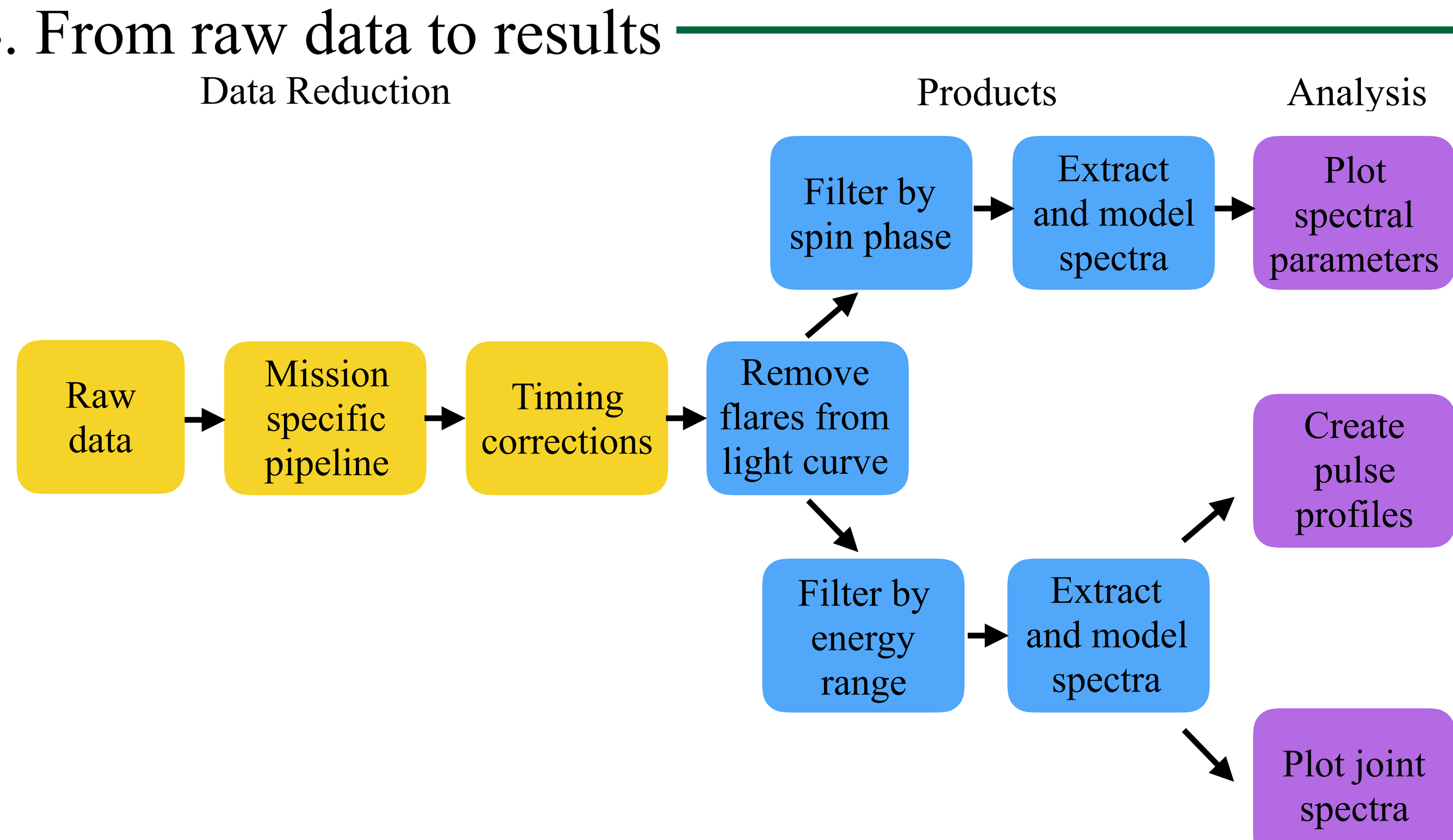

Figure 4: Schematic diagram of the data reduction and analysis process for this project.

5. Pulse profiles and joint spectra

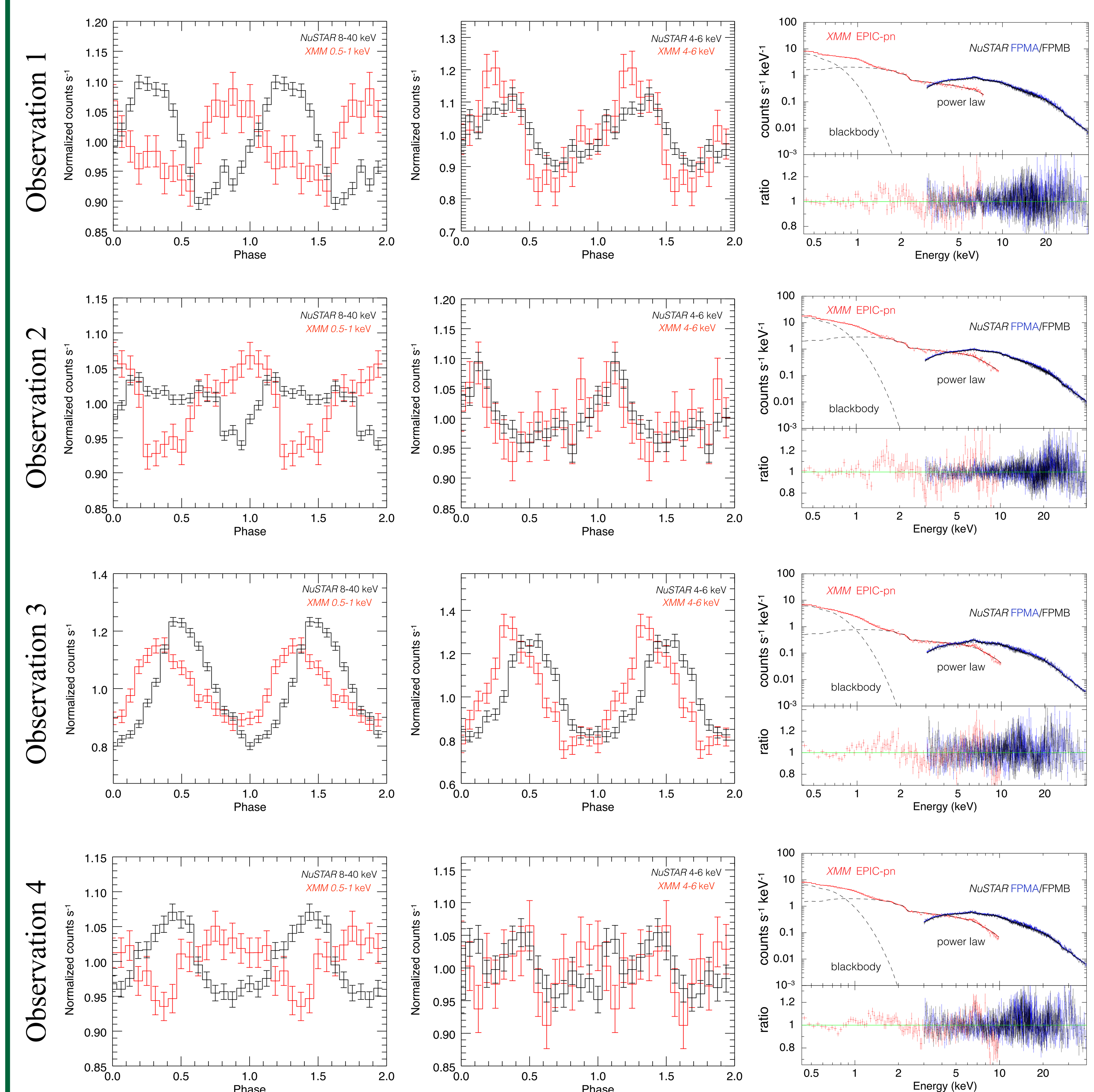

Figure 5: *Left column* - pulse profiles of the *NuSTAR* 8-40 keV signal (black) and the *XMM-Newton* 0.5-1 keV signal (red) for each observation. **Notice the change in the relative phase, indicating the precession of the accretion disk.** *Middle column* - pulse profiles of the *NuSTAR* 4-6 keV signal (black) and the *XMM-Newton* 4-6 keV signal (red) for each observation. Because these signals are observed simultaneously in the same energy range, the pulses are in phase. *Right column* - a joint spectrum for each observation, where *NuSTAR* FPMA/FPMB spectra are shown in blue and black respectively, and the *XMM-Newton* spectrum is shown in red. The power law and thermal blackbody (kT ~ 0.15 keV) components of each model are shown as black dashed lines. Four emission lines included in the model are not plotted. The bottom panels of the spectra show the ratio of data to model, thus indicating the goodness of fit.

6. Conclusions and future work

Plotting pulse profiles of the high energy and low energy signals allows us to see the relative phase changes between the hard pulsar beam and the soft reprocessed photons. The complete shift in relative phase, seen in the left column of Figure 5, indicates that the accretion disk has precessed completely around the pulsar.

Future work on this project includes performing pulse-phase spectroscopy, refining the spectral models, and extracting spectral parameters for each observation. The spectral parameters will allow us to determine the luminosity from the blackbody and power law components separately. We will reconstruct these luminosities using a simple warped disk model (e.g., Hickox & Vrtilek 2005) to visualize the shape of the accretion disk and the kinematics of its precession.

References and Acknowledgements

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