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New Techniques for Understanding Rapid X-Ray Variability from Compact Objects

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Summary

Compact objects like stellar-mass black holes and neutron stars are the final remnants of core-collapse supernovae of massive stars. In the general relativistic framework, compact objects are dense enough to significantly warp spacetime. By studying emission from very close to the compact object, we can decipher the effects of strong-gravity on physical processes, and test general relativity in the strong-field limit. Improving our understanding of the strong gravitational regime will help to advance models of supermassive black holes in active galactic nuclei, compact object mergers, gamma-ray burst environments, and gravitational waves. Moreover, the inner cores of neutron stars are theorized to be denser than an atomic nucleus, and these supra-nuclear-density conditions cannot be re-created in a laboratory on Earth. As such, a major goal of the field is to determine the equation of state of neutron star matter. Modelling emission from the surfaces of neutron stars can place constraints on the equation of state, with implications for the extreme limits of nuclear physics, particle physics, and condensed matter physics.

One of the best laboratories to study compact objects is low-mass X-ray binaries (LMXBs), in which the compact object accretes from a low-mass stellar binary partner. For LMXBs in outburst, viscous heating in the accretion disk causes the accreting plasma to glow brightly in the X-rays as it falls down the potential well of the compact object. The X-rays are dominated by emission from the immediate vicinity of the compact object, in the strong-field gravity regime. The two primary analysis tools to study X-ray emission from LMXBs are spectroscopy and timing. Spectroscopy informs us of the physical processes and components present in the inner region of the LMXB, while timing informs us of dynamical changes in these systems.

There is a plethora of rapid sub-second variability in the X-ray light curves from accreting LMXBs, and a growing toolbox of analysis techniques and algorithms to apply to such phenomena. The two kinds of variability that are studied in this thesis are quasi-periodic oscillations (QPOs) and coherent X-ray burst oscillations. QPOs are a probe for studying physical processes in the inner regions of LMXBs, and X-ray burst oscillations are used to determine the masses and radii of neutron stars to constrain the neutron star equation of state. Of the novel analysis techniques, the one featured most

prominently in this thesis is X-ray spectral-timing, and specifically our method for QPO-phase-resolved spectroscopy. Spectral-timing analysis combines spectroscopy and timing simultaneously to take advantage of energy-dependent Fourier amplitudes and phases in the data. With this, we can deduce the temporal relationships between spectral components and break degeneracies in QPO emission models. The other new analysis technique featured in this thesis is an evolutionary optimization algorithm. When applied to models of X-ray burst oscillations, it is able to explore the degeneracies in the model parameter space more efficiently than other popular algorithms. With these new analysis techniques, we are able to get more out of the data and gain a better understanding of compact objects.

In Chapter 2, we present a novel spectral-timing technique to do phase-resolved spectroscopy of QPOs that tracks the variations of spectral parameters with QPO phase. We apply this new technique to the fleeting Type B low-frequency QPO from the black hole GX 339–4 during its 2010 outburst. We find that the blackbody emission has a small variation ($\sim 1.4\%$ fractional rms) that leads the large power-law variation ($\sim 25\%$ fractional rms) by ~ 0.3 in relative phase. We also find that the variable blackbody is cooler and larger than the inner edge of the accretion disk. From these results, we infer that a large-scale-height ('jet-like') Comptonizing region precesses during a QPO cycle, illuminating and heating azimuthal regions of the inner accretion disk. There is debate regarding the location of the Comptonizing region, and our results suggest that the Comptonizing region in this black hole is linked to the base of the radio jet. Furthermore, we find that the QPO lag-energy spectrum can be reproduced by *periodic* variations of the low- and high- energy spectral components that are shifted out of phase with each another.

In Chapter 3, we use ray-tracing to simulate pulse profiles of thermonuclear burst oscillations from an accreting neutron star. We then fit these with an evolutionary optimization algorithm (similar to a genetic algorithm, with more generalized features) to assess how well we could recover the input parameters. This application of an evolutionary optimization algorithm to burst oscillation pulse profile modelling is the first of its kind in the literature. For the regions of parameter space sampled by our tests, the mass and radius fits are accurate (average bias compared to the true value) to $\leq 5\%$, with an uncertainty (statistical error, including degeneracies among the fit parameters) of $\leq 7\%$ in mass and $\leq 10\%$ in radius. While the parameter spaces of all the models tested have some degeneracy, we find that synthetic pulse profiles with significant asymmetry and large amplitudes are the best-constrained. If these results could be obtained with real data from a large-area, high-throughput X-ray timing instrument like *eXTP* or *STROBE-X*, they will produce definitive tests that rule on the validity of equation of state models.

In Chapter 4, we apply our phase-resolved spectroscopy technique to a lower kilohertz (kHz) QPO from the neutron star 4U 1608–52 during its 1996 outburst. We find evidence for significant variations in the shape of the Comptonized blackbody spectral component, like a nearly 10% rms variation in the photon index. The seed blackbody temperature changes by only a few percent, giving a total QPO spectrum that pivots at low energies with the dominant variation happening in the hard X-rays. The small time lags (few tens of microseconds) cannot be reproduced by the changing amplitude of the parameter variations alone, but by including small (few percent) phase lags in the parameter variations. These results are interpreted as a 'breathing' oscillation in the neutron star boundary layer (where the accretion disk meets the neutron star surface). Finer spectral and temporal resolution of the lower kHz QPO from, e.g., *NICER* or *STROBE-X*, would allow us to precisely determine the location of the seed blackbody and the internal spectral shape changes of the boundary layer, to better understand the physics of this 'breathing' oscillation.

Finally in Chapter 5, we carry out spectral-timing analysis of the Type B low-frequency QPO seen by *NICER* in the new black hole transient MAXI J1535–571 in the autumn of 2017. We discover a weak Type B QPO in the soft spectral state of the outburst and we compute its energy-dependent cross-spectrum amplitude, lag-energy spectrum, cross-correlation function, and phase-resolved ratio spectra. The lag-energy spectrum has a similar shape but opposite sign as compared to the Type B QPO lags in Chapter 2, and the ratio spectra indeed show that the soft X-rays *lag* the hard X-rays by $\sim 27\%$ of a QPO cycle. *NICER*'s superb CCD energy resolution of the soft X-rays tracks the tiny blackbody variations with QPO phase, and the completed spectral calibration of *NICER* in the future will allow us to fit detailed models to the QPO-phase-resolved spectra. While we find no evidence of a changing iron line profile in the ratio spectra, a larger-area X-ray observatory like *STROBE-X* would place much stricter upper limits on the presence of this reflection component in the QPO emission.