Rapid Spectral Variability of Compact Objects in X-Ray Binary Systems

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Introduction

The stars in our universe live lifetimes, evolve, and die as we humans do. At the end of their lifecycle, depending on their mass, they shed their outer layers, either calmly via winds or more cataclysmically as explosions like supernovae, to leave behind their degenerate cores as a **compact object: a white dwarf (WD), neutron star (NS), or black hole (BH).** These compact objects are so dense that they can warp the immediate spacetime around them. **This is a direct consequence of Einstein's Theory of General Relativity (GR).** From Sir Eddington and Sir Dyson's gravitational lensing observations from the 1919 solar eclipse (Dyson et al. 1923) to the 2015 LIGO detection of gravitational waves from compact object mergers (Abbott et al. 2016), we have seen the evidence that Einstein's theories truly do predict the general behavior of the surroundings of massive objects in our Universe. Still, there is more to be understood, within the bigger picture that we already have. **How does strong-field gravity affect the geometry of accretion disks and matter within its potential well? How, if at all, does it influence the evolution and behavior of celestial objects in its regime?** Studying compact objects can reveal the answers to these questions.

One of the best laboratories to study strong-field gravity is the inner 100s of kilometers around stellar-mass BHs in low-mass X-ray binaries (LMXBs), binary systems in which the compact object has a low-mass stellar companion, as depicted in figure one. The *Neutron star Interior Composition Explorer* (*NICER)*, installed on the International Space Station in 2017, is an important soft X-ray telescope that can be used in time domain analysis of these LMXBs. The X-ray light curves of these binary systems, from data taken from a telescope like *NICER* or *NuSTAR,* show variability on timescales from milliseconds to months — the shorter (sub-second) variability can appear as quasi-periodic oscillations (QPOs), which may be produced by general relativistic effects. Current theories for QPOs include precession of the Comptonized hot inner accretion flow that is present around the compact object, as seen in figure two, or even the precession of its relativistic jets. **The leading theory today is that general relativistic Lense-Thirring precession is the origin of low-frequency QPOs** (0.1-20 Hz; Stella & Vietri 1998; Ingram et al. 2009; Ingram et al. 2016), as most commonly seen from modulating iron lines from the corona around the compact object. Placing constraints on the QPO emission mechanism will help to answer the questions we have about GR and LMXBs.

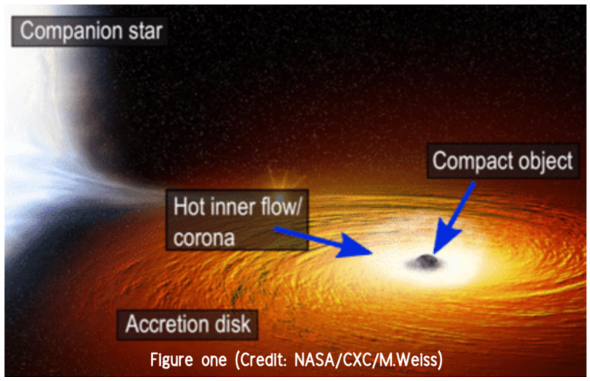

Figure one (Credit: NASA/CXC/M.Weiss)

Proposed Research

To probe the questions that we have about GR, LMXBs, and QPOs, I will select bright X-ray targets and use *NICER* or *NuSTAR* archival data and submit proposals to get new data. The analysis of this data often includes Fourier analysis (in Python, using existing and developing packages) which due to working in the time-domain. I have expertise in this analysis, as my Post-Baccalaureate position at Michigan State University has included analysis of a LMXB, MAXI J1820+070 which is a BH transient, and have a paper in preparation.

Comparing to multi-wavelength observations will also help constrain the area of emission of QPOs. For example, by observing in radio, we can determine if the compact object has relativistic jets (they emit in radio due to synchrotron radiation, Fender et al. 2004) and compare against the observed signals. If the object has jets and a strong QPO, we can infer that the QPO emission mechanism and the jet mechanism are related. This can be verified by long-term observation of the object as it transitions from a Comptonization-dominated to a disk-dominated state and when the jets turn off (Fender et al. 2009). Phase-resolved spectroscopy, or fitting spectra at different phases in the QPO "quasi-period", can give more insight into the physical properties of the material around the compact object, like accretion disk size and temperature, corona height and geometry, and the connection between them. Another portion of the project will be performing statistical analyses to constrain the spectral parameters and using them to help build useful models of geometry of the inner region near the compact object, thus helping place constraints on the QPO emission mechanism and helping our understanding of GR. This research goes beyond the XRBs as inflows and outflows from XRBs are analogous to accretion and feedback in active galactic nuclei (AGN), of which impact other astrophysical subfields, like stellar formation and galactic evolution. Understanding these phenomena will greatly impact our understanding of the universe around us.

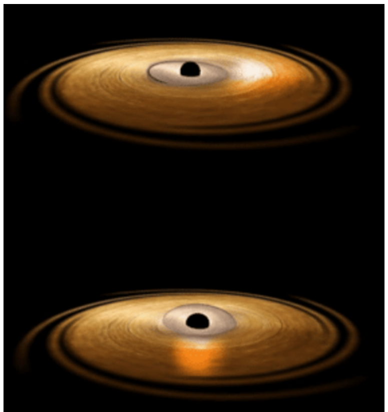

Figure two (Credit: ESA/ATG medialab/ A. Ingram)

Broader Impacts

While this research will lead to important and necessary advancements to our understanding of GR, high energy astrophysics, and many other sub-fields of physics, there is much to be said about the impacts that can be made outside of the XRB community too. The most immediate thing I will do is contribute to open source software that other scientists, even citizen scientists, can use to do similar research for themselves. I have **already contributed to Python packages used in data analysis such as Stingray**, used for X-ray timing analysis (Huppenkothen et al. 2019), and I will continue to contribute back to the open source reproducible science community.

Within the academic community, I will have a unique place within the X-ray subfield to contribute and push forth new and upcoming X-ray missions like *XRISM*, *STROBE-X, Lynx*, and *Athena*. These missions will lend themselves to answering "the highest priority science questions about the formation, evolution, and accretion processes of black holes, the nature of dense matter and gravity, and a wide range of cosmic explosions" that still remain in the field[1]. They will need not only knowledge about compact objects and accretion, but also new data reduction and analysis tools created, science communication, and outreach development, all of which I will provide. The NSF Graduate Research Fellowship Program will be the first step in achieving my goals as a researcher, thus turning these plans into actions.

References

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[1] https://gammaray.nsstc.nasa.gov/Strobe-X/