Research Statement (NSF GRFP 2015): Rhondale Tso

My proposed research addresses the theoretical understanding of potential electromagnetic (E&M) counterparts to compact binaries as they are driven to inspiral and eventually merge due to gravitational wave (GW) emission. *What are these signatures, how do they come about, and what does it mean for GW analysis?* Efforts are to concentrate on E&M fields associated with these binaries and their implications for GW analysis. The goal is that such studies will provide insight on potential luminous sources to GW observations, aiding in the multi-messenger astronomy mission of the LIGO-Virgo Collaboration.

As mentioned in my personal statement, the Laser Interferometer Gravitational-wave Observatory (LIGO) and Virgo are laboring towards first detections of GW transients, having the potential to open a new field of astronomy. The European Space Agency's future eLISA[1] mission has similar goals but will probe the low-frequency regime of extreme mass ratio and massive black hole (BH) inspirals [1]. This is in contrast to the high-frequency, stellar-mass BH binaries of LIGO detectors. Predicted by General Relativity (GR), the essence of GWs rests on the idea that propagating deformations of spacetime, produced from accelerating masses, carry energy away from their sources. My ongoing work focuses on these sources being compact objects, dead stars such as BHs and neutron stars (NSs), orbiting each other in binary systems. As these objects orbit, spin, and merge, GWs emanate from their motions. In recent months my efforts shifted, from studying eccentric binaries, to a rigorous study of the E&M fields associated with compact objects, BHs in particular. My focus will remain in this concentration for the first years of graduate school.

What are these signatures and how do they come about? Analysis of a binary inspiral is primarily accomplished through a combination of semi-analytic and numerical methods in solving the dynamical equations of GR. The predominant semi-analytic approach is the post-Newtonian formalism, an approximative method linearizing the GR field equations, which ultimately surfaces as the sequential appending of corrections to conventional Newtonian dynamics. Although successful in describing the inspiral phase of a binary, this approximation breaks down as merging is approached, where orbital velocities approach the speed of light and spacetime curvature increases rapidly. In this respect, numerical techniques in solving the equations of GR have given birth to a new subfield: numerical relativity, an area of specialty for the *Simulating eXtreme Spacetimes* (SXS) group [2]. E&M fields associated with highly magnetized neutron stars and/or accretion disks are expected to present interesting results as the objects approach this merging stage. In collaboration with Dr. Saul A. Teukolsky at Cornell University and the researchers of the SXS group, I hope to extend my work, which is currently being established from first principles of GR. The plan is to incorporate realistic astrophysical environments, simulations of binary mergers, and plasma accretion in the extremely relativistic regime of BH-NS, NS-NS systems. Here I will study the dynamics of E&M fields as the companions merge and, for systems involving a NS, the repercussions from the NS's tidal disruption. Through the Blandford-Znajek mechanism, jets were shown to be powered through an electromotive force (emf) induced by a rotating BH in a strong magnetic field [3]. Recently a BH-NS binary was shown to exhibit similar properties, as an emf is generated and a circuit is established via the BH-NS system, field

[1] evolved/evolving Laser Interferometer Space Antenna

lines, and charged particle flow [4]. Such a scenario has exhibited potential sources of E&M complements to the GW inspiral/merger signal. My efforts are to observe how these physical effects behave when approximations breakdown and thorough investigations are left to numerical relativity during merger. Experiences in programming, research in numerically solving charged particle dynamics about a rotating BH, and prior study of the GW emission process makes me well-prepared to tackle such a problem.

What do E&M signatures mean for GW analysis? Prior experience discussed in my personal statement also highlights previous work in testing relativity and GW error estimation techniques. Here my work with LIGO members, MIT postdoc Salvatore Vitale and Embry-Riddle professor Michele Zanolin, can also be extended. Continued work on my undergraduate thesis has culminated in a preprint to be submitted for publication [5]. Our work focused on a frequentist approach in error estimation of the parameters controlling a GW's deviation from that of GR. Possessing a reliable template for E&M signatures associated with GW emission will provide new avenues of waveform analysis for the LIGO-Virgo Collaboration. Future work will extend prior results in our frequentist studies by *resolving* the GW signal through multiple detections and quantifying the degree to which multiple detections can impose further constraints on non-GR theories. Inclusion of E&M counterparts will supplement such studies, for example, such efforts will provide a reduction in the parameter space, improving estimates of variables describing a waveform. A quantitative study of the benefits to be had from multi-messenger astronomy and possible constraints on non-GR theories will be firmly instituted for future studies of modified theories of gravity.

Successful completion of this work are summarized as follows: 1) successfully simulating E&M field lines' dynamics up to and beyond the post-merger phase, 2) modeling potential E&M counterparts from such dynamics, and 3) quantitative study of additional constraints imposed on non-GR theories through cross-disciplinary (GW and E&M) observations. Timeline for 1 and 2 is set for two years, with additional questions set to be answered throughout the third year. Concurrently, work will be done on 3, which is given three years since much of the work will be heavily collaborative.

As physicists and astronomers approach the first direct detection of GWs, it is imperative optimal search strategies are developed and relevant astrophysical environments are well-studied. Our work is the culmination of over a century of dedicated research in GR and will set the stage for years to come.

References

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