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Report on my 2017 visit to YITP as a Visiting Professor

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Abstract. I summarize my research and teaching activities during my three-month visit to the Yukawa Institute for Theoretical Physics from March 2017 to June 2017. This visit was support by the International Research Unit of Advanced Future Studies.

Keywords: numerical relativity, neutron star mergers, core-collapse supernovae, gravitational waves, black holes, advanced future studies, Python

1. Personal Note

I wish to express my gratitude to YITP faculty and staff for their great hospitality during my three-month stay at YITP as a Visiting Professor. I wish to thank the International Research Unit of Advanced Future Studies for their kind support of my visiting professorship.

It is always a great pleasure to visit YITP and interact with its faculty, postdocs, students, and staff. Kyoto and YITP have become very important for me – scientifically and personally. Now, at the end of my second long-term visit (after my three-month visit in 2016), I am already looking forward to my next opportunity to visit YITP!

Kyoto, June 12, 2017

Christian Ott

2. Research Completed at YITP

I completed five research projects during my stay at YITP. Many of these were relatively short-term projects that involved substantial work while I was at YITP.

2.1. A Numerical Relativity Waveform Surrogate Model for Generically Precessing Binary Black Hole Mergers

(with Jonathan Blackman, Scott Field, Mark Scheel, Chad Galley, Michael Boyle, Lawrence Kidder, Harald Pfeiffer, and Bela Szilagyi)

In this project with my Caltech graduate student Jonathan Blackman we constructed a fast and efficient binary black hole waveform model for LIGO gravitational wave data analysis. This model uses so-called reduced-order modeling techniques to generate gravitational waveforms using an efficient basis made up of waveforms from actual numerical relativity simulations. The waveform model is extremely efficient: While a numerical relativity simulation requires weeks to months to run, the waveform model can produce a waveform in less than a tenth of a second. Having such fast evaluations is essential for gravitational wave data analysis and parameter estimation.

This work by Blackman et al. is particularly notable, because it is the first to cover the full 7-dimensional parameter space: mass ratio and three spin components for each black hole. Previous models could predict gravitational waveforms only in lower-dimensional subspaces. The range in mass ratio that our model covers goes from 1 (equal mass) to 2 (the more massive black hole is twice as massive than the less massive black hole) and in dimensionless Kerr spin from 0 to 0.8. Future work will be directed toward extending the model to higher mass ratios and higher spins.

The resulting paper has been submitted for publication in Physical Review D as Blackman et al. 2017. It is available on arXiv as arXiv:1705.07089, https://arxiv.org/abs/1705.07089. The paper has been assigned YITP report number YITP-17-44.

2.2. Gravitational Waves from Binary Black Hole Mergers Inside of Stars

(with Joseph Fedrow, Ulrich Sperhake, Jonathan Blackman, Roland Haas, Christian Reisswig, and Antonio de Felice)

This project is a true YITP project – it was conceived, started, carried out, and completed at YITP. Its lead author Joseph Fedrow is a YITP graduate student working with Sasaki-san and me.

We carried out a set of controlled numerical experiments to investigate the effect of stellar density gas on the coalescence of binary black holes (BBHs) and the resulting gravitational waves (GWs). This investigation is motivated by the proposed stellar core fragmentation scenario for BBH formation and the associated possibility of an electromagnetic counterpart to a BBH GW event. We employ full numerical relativity coupled with general-relativistic hydrodynamics and set up a 30 + 30 solar mass BBH (motivated by GW150914) inside gas with realistic stellar densities. Our results show that at densities $\gtrsim 10^6$ - 10^7 g cm^{-3} dynamical friction between the BHs and gas changes the coalescence dynamics and the GW signal in an unmistakable way. We show that for GW150914, LIGO observations conclusively rule out BBH coalescence inside stellar gas of $\gtrsim 10^7$ g cm^{-3}. Typical densities in the collapsing cores of massive stars are in excess of this density. This excludes the fragmentation scenario for the formation of GW150914.

The resulting manuscript has been submitted for publication to Physical Review Letters. It is available on arXiv as arXiv:1704.07383, https://arxiv.org/abs/1704.07383 . The paper has been assigned YITP report number YITP-17-40.

2.3. Signatures of Hypermassive Neutron Star Lifetimes on r-Process Nucleosynthesis in the Disk Ejecta from Neutron Star Mergers
(with Jonas Lippuner, Rodrigo Fernandez, Luke Roberts, Francois Foucart, Daniel Kasen, and Brian Metzger)

Some of the heaviest chemical elements in the universe are made by the so-called rapid neutron capture process (r-process). The r-process most likely site are neutron star mergers (mergers of two neutron stars or of a neutron star with a black hole). In the case of double neutron star mergers, often a hypermassive merger remnant survives for an extended period of time before collapse to a black hole. Since this hypermassive neutron star (HMNS) is very hot, it is a very bright source of neutrinos that irradiate the material in the accretion disk surrounding it.

In this study with my Caltech graduate student Jonas Lippuner, we investigate the nucleosynthesis of heavy elements in the winds ejected by accretion disks formed in neutron star mergers. We compute the element formation in disk outflows from HMNS remnants of variable lifetime, including the effect of angular momentum transport in the disk evolution. We employ long-term axisymmetric hydrodynamic disk simulations to model the ejecta, and compute r-process nucleosynthesis with tracer particles using a nuclear reaction network containing ~8000 species. We find that the previously known strong correlation between HMNS lifetime, ejected mass, and average electron fraction in the outflow is directly related to the amount of neutrino irradiation on the disk, which dominates mass ejection at early times in the form of a neutrino-driven wind. Production of lanthanides and actinides saturates at short HMNS lifetimes ($\lesssim$10 ms), with additional ejecta contributing to a blue optical kilonova component for longer-lived HMNSs. We find good agreement between the abundances from the disk outflow alone and the solar r-process distribution only for short HMNS lifetimes ($\lesssim$10 ms). For longer lifetimes, the rare-earth and third r-process peaks are significantly under-produced compared to the solar pattern, requiring additional contributions from the dynamical ejecta. The nucleosynthesis signature from a spinning black hole (BH) can only overlap with that from a HMNS of moderate lifetime ($\lesssim$60 ms). Finally, we show that angular momentum transport not only contributes with a late-time outflow component, but that it also enhances the neutrino-driven component by moving material to shallower regions of the gravitational potential, in addition to providing additional heating.

The resulting manuscript has been submitted to Monthly Notices of the Royal Astronomical Society. It is available on arXiv.org as arXiv:1703.06216, https://arxiv.org/abs/1703.06216 . The paper has been assigned YITP report number YITP-17-26.

2.4. A Detailed Comparison of Multi-Dimensional Boltzmann Neutrino Transport Methods in Core-Collapse Supernovae
(with Sherwood Richers, Hiroki Nagakura, Josh Dolence, Kohsuke Sumiyoshi, Shoichi Yamada)

This project is a US-Japan collaboration to compare two different exact neutrino transport formulations: the so-called Discrete Ordinates approach and the Monte Carlo approach in the context of core-collapse supernova explosions from massive stars.

The mechanism driving core-collapse supernovae is sensitive to the interplay between matter and neutrino radiation. However, neutrino radiation transport is very difficult to simulate, and several radiation transport methods of varying levels of approximation are available. We carefully compare for the first time in multiple spatial dimensions the discrete ordinates (DO) code of Nagakura, Yamada, and Sumiyoshi and the Monte Carlo (MC) code Sedonu, under the assumptions of a static fluid background, flat spacetime, elastic scattering, and full special relativity. We find remarkably good agreement in all spectral, angular, and fluid interaction quantities, lending confidence to both methods. The DO method excels in determining the heating and cooling rates in the optically thick region. The MC method predicts sharper angular features due to the effectively infinite angular resolution, but struggles to drive down noise in quantities where subtractive cancellation is prevalent, such as the net gain in the protoneutron star and off-diagonal components of the Eddington tensor. We also find that errors in the angular moments of the distribution functions induced by neglecting velocity dependence are sub-dominant to those from limited momentum-space resolution. We briefly compare directly computed second angular moments to those predicted by popular algebraic two-moment closures, and find that the errors from the approximate closures are comparable to the difference between the DO and MC methods. Included in this work is an improved Sedonu code, which now implements a fully special relativistic, time-independent version of the grid-agnostic Monte Carlo random walk approximation.

As part of this project we make the new version of the Sedonu code available as open source at https://bitbucket.org/srichers/sedonu and provide the results of our study as open data at https://zenodo.org/record/807765. The resulting manuscript has been submitted for publication in the Astrophysical Journal Supplemental Series. It is available on arXiv.org as arXiv:1706.06187 https://arxiv.org/abs/1706.06187. The paper has been assigned YITP report number YITP-17-61.

2.5. A New Open-Source Nuclear Equation of State Framework based on the Liquid-Drop Model with Skyrme Interaction
(with Andre da Silva Schneider and Luke Roberts)

In this interdisciplinary collaboration between nuclear physicists and astrophysicists, we developed a new nuclear equation of state (EOS) framework that can generate thermodynamically consistent EOS for neutron star merger and core-collapse supernova simulations.

The EOS of dense matter is an essential ingredient for numerical simulations of core-collapse supernovae and neutron star mergers. thee properties of matter near and above nuclear saturation density are uncertain, which translates into uncertainties in astrophysical simulations and their multi-messenger signatures. Therefore, a wide range of EOSs spanning the allowed range of nuclear interactions are necessary for determining the sensitivity of these astrophysical phenomena and their signatures to variations in input microphysics. We present a new set of finite-temperature EOSs based on experimentally allowed Skyrme forces. We employ a liquid drop model of nuclei to capture the non-uniform phase of nuclear matter at sub-saturation density, which is blended into a nuclear statistical equilibrium EOS at lower densities. We also provide a new, open-source code for calculating EOSs for arbitrary Skyrme parametrizations. We then study the effects of different Skyrme parametrizations on thermodynamical properties of dense astrophysical matter, the neutron star mass-radius relationship, and the core collapse of 15 and 40 solar mass stars.

The new EOS code and pregenerated tables are available at https://stellarcollapse.org/SROEOS. The resulting manuscript will be submitted to Physical Review C in late June 2017. The manuscript has been assigned YITP report number YITP-17-32.

3. Teaching at YITP

Since YITP has been supporting me so generously and since the YITP community has given me such a warm welcome, I felt I needed to return the favor in some way. Recently, the open-source Python programming language has become very popular all across science, engineering, and in the technology industry. Python is the new lingua franca for scientific computing and data science (big data).

I have been using Python in research and teaching for about 15 years. I am intimately familiar with its capabilities. Hence, I decided to offer a short course to YITP students, postdocs, and faculty titled "Introduction to Python for Scientific Computing". One novel approach I took was to use cloud computing in the lecture: Instead of each participant having to struggle installing Python in their computer, I ran a "Jupyter Notebook" (http://jupyter.org/) server in the Amazon AWS cloud computing platform and the students could work in Python simply with their web browser. This made the experience very smooth and free of individual software installation issues.

The course comprised four lectures and I involved YITP graduate student Joseph (Joey) Fedrow in preparing and holding the lectures. This gave Joey valuable experience. In lecture 1, I introduced the Python programming language and took the participants on a guided tour with hands-on examples. In lecture 2, I introduced the Python modules NumPy and Matplotlib for scientific computing and plotting. Lecture 3 was dedicated to making high-quality figures for publications with Python. Finally, in Lecture 4, we went into more details on making high-quality figures and then took a close look at the scientific computing tools provided by the SciPy package (interpolation, fitting, Fourier transforms, optimization/root finding etc.).

I believe the lectures were well received. They certainly were quite well attended. We had about 15 to 20 participants in each lecture. The lecture notes, examples, presentation slides, and Jupyter Notebooks are available at https://bitbucket.org/hypercott/python-yitp .

4. Brief Overview of New Research Started at YITP

I have started a number of new projects involving YITP researchers during my visit. They are still in their early stages. I provide brief summaries in the following.

4.1. Numerical Relativity Simulations of Spinning Black Holes with the Z4c Evolution System

(with Joseph Fedrow and Masaru Shibata)

The BSSN (including S for Shibata-san and N for Nakamura-san, both YITP/Kyoto faculty) formalism of numerical relativity has been extremely successful in permitting long-term stable numerical relativity simulations of vacuum binary black hole and matter spacetimes. However, it is well known empirically that BSSN evolutions become unstable for highly-spinning black holes (and even for single high-spin black holes). The Z4c evolution system builds upon BSSN, but introduces auxiliary variables and equations that change the properties of the evolution system in such a way to provide greater numerical stability and accuracy.

In this project, which is led by YITP graduate student Joseph Fedrow, we are investigating simulations of rapidly spinning single black holes using Z4c. We are comparing Z4c and BSSN simulations to understand if and why Z4c provides longer-term stable high-spin evolutions.

4.2. A Review of Core-Collapse Supernova Simulations

I have been asked by the online reviews series Living Reviews in Computational Astrophysics to write a review on simulations of core-collapse supernovae. While at YITP, I took first steps in preparation for this review, which will be an extensive work and will summarize the history and the state of the art of the field. I have been fortunate to work with YITP graduate student Joey Fedrow, who has been helping me with visualizations and figures for the review.

4.3. A Parameter Study of 3D Core-Collapse Supernovae

Using the new set of nuclear equation of state (EOS) tables generated as part of the study described in Section 2.5 of this report, I have started a set of general-relativistic 3D core-collapse supernova simulations to investigate the role of the nuclear EOS on the neutrino mechanism for core-collapse supernovae. This study is in its early stages and involves my Caltech postdoc Andre da Silva Schneider, who visited me at YITP in May 2017.