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Report on my 3-month visit to YITP

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Abstract. I summarize my research activities during my 3-month visit to the Yukawa Institute for Theoretical Physics from January to March 2016.

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

1. Personal Note

I wish to express my gratitude to YITP faculty (in particular Sasaki-san and Shibata-san) and staff for their great hospitality during my ~3-month visit. I have come to appreciate YITP as a very special place in the world: not only do YITP faculty and staff produce some of the most important and exciting scientific results, they also create an environment at YITP that is welcoming and extremely scientifically stimulating. I felt welcome at YITP from day one and am honored by and grateful for the hospitality that I have received.

Everybody made YITP and Kyoto feel like a home away from home for me. I will always cherish my memories of the past three months and I am excited to come back in the future!

Kyoto, March 30, 2016

Christian Ott

2. Research Completed at YITP

I completed six research projects during my stay at YITP. Many of these were relatively short-term projects that involved substantial work while I was at YITP. However, one project started as early as 2009 and I was very happy to have the time and ability to concentrate on completing it while at YITP.

2.1. Dynamical Mass Ejection from Binary Neutron Star Mergers

(with David Radice, Filippo Galeazzi, Jonas Lippuner, Luke Roberts, and Luciano Rezzolla)

In this project with my postdocs Radice and Roberts and my graduate student Lippuner (and external collaborators Galeazzi and Rezzolla), we investigated the dynamical ejection of neutron star matter when two neutron stars collide in a neutron star merger. It is important to understand the amount and chemical composition of these ejecta, since they are believed to be the primary source of very heavy neutron-rich nuclei that are formed via the rapid neutron capture process (r-process). Furthermore, the composition of the dynamical ejecta plays a role in determining the features of the electromagnetic afterglow "kilonova" emission from the merger remnant. Our results confirm previous studies that suggested that eccentric mergers eject more matter than the more common quasicircular mergers. We also find, as expected and previously shown by the Kyoto group, that the composition of the dynamical ejecta is sensitive to neutrino cooling and heating effects. However, in contrast to previous work, we do not find that neutrino heating can drive up the electron fraction sufficiently to produce the lightest "first peak" r-process nuclei. These must come from some other source or from the viscously driven or neutrino-driven disk wind in the post-merger evolution.

The resulting paper has been accepted for publication in MNRAS as Radice et al. 2016. It is available on arXiv as arXiv:1601.02426, http://arxiv.org/abs/1601.02426.

2.2. The Influence of Neutrinos on r-Process Nucleosynthesis in the Ejecta of Black Hole--Neutron Star Mergers

(with Luke Roberts, Jonas Lippuner, Matt Duez, Josh Faber, Francois Foucart, James Lombardi, Sandra Ning, and Marcelo Ponce)

This paper comes out of the Simulating eXtreme Spacetimes (SXS) collaboration that was originally started by Kip Thorne (Caltech) and Saul Teukolsky (Cornell). SXS now includes researchers at Caltech,
Cornell, CITA (U of Toronto), The Albert Einstein Institute, UC Berkeley, Washington State University, and Calstate Fullerton. My postdoc Roberts (NASA Einstein Fellow) and my graduate student Jonas Lippuner post-processed simulated particle trajectories of material ejected from black hole -- neutron star (BHNS) merger simulations carried out with the SXS merger code SpEC. BHNS mergers at realistic mass ratios and black hole spins tend to eject more neutron star material than double neutron star mergers. Hence, they may be the primary source of very neutron rich nuclei in the universe. Our results show that all considered BHNS cases produce a very robust heavy (2nd and 3rd peak) r-process. When including irradiation by neutrinos from a post-merger disk, we find that neutrino absorption can drive up the yield in the first peak, but not sufficiently to explain the solar abundance pattern of r-process nuclei. Again, a
different source (perhaps core-collapse supernovae) for the lightest r-process elements may be needed.

The resulting paper has been submitted to MNRAS as Roberts et al. 2016. It is currently under review and available on arXiv as arXiv:1601.07942, http://arxiv.org/abs/1601.07942.

2.3. Numerical Simulations of Stellar Collapse in Scalar-Tensor Theories of Gravity
(with Davide Gerosa and Uli Sperhake)

In this project with my collaborator Sperhake (Cambridge) and his graduate student Gerosa (who will join Caltech as a postdoc in the fall), we extended my groups spherically-symmetric (1D) general relativistic core collapse code GR1D to include a scalar field in the gravitational sector that feeds back on the dynamics of the collapse evolution. The scalar degree of freedom introduces *monopole* gravitational waves that, if measured by LIGO, KAGRA, and Virgo, would be very strong evidence for a scalar component of gravity. Our goal was to predict monopole gravitational waves and study their strength and morphology as a function of scalar-field parameters and progenitor star characteristics.

We chose a formulation with a coupling function F that depends on two parameters alpha_0 and beta_0 and that recovers standard Brans-Dicke theory with omega_BD = (1-6 alpha_0^2)/(2 alpha_0^2) and beta_0 = 0. alpha_0 and \beta_0 have been constrained observationally by weak-field tests, but the currently remaining unconstrained parameter space is still (astro)physically interesting.

We carried out a large set of 1D stellar collapse simulations and found that the scalar field (with parameters in the still allowed parameter space) has negligible influence on the collapse dynamics itself. For standard, neutron-star forming core collapse events, the emitted scalar gravitational waves are unlikely to be seen by second-generation gravitational wave observatories, even if the event occurs within the Milky Way. The situation is different for black hole forming core collapse: in this case, the compactness of the protoneutron star is so large that nonlinear effects come into play, leading to what is called *spontaneous scalarization*, just before black hole formation. In this process, the scalar field amplitude suddenly shoots up and sends out a strong pulse of scalar gravitational waves. This signal from a galactic event would be detectable even by current second-generation gravitational wave observatories and a non-detection would add interesting constraints on scalar-field parameters.

The resulting paper has been submitted to CQG as Gerosa et al 2016. It is currently under review and available on arXiv as arXiv:1602.06952, http://arxiv.org/abs/1602.06952. It has been assigned YITP report number YITP-16-14.

2.4. The One-Armed Spiral Instability in Neutron Star Mergers and its Detectability in Gravitational Waves
(with David Radice and Sebastiano Bernuzzi)

In this project with my postdoc Radice and former postdoc Bernuzzi (now junior faculty at Parma), we carried out fully general-relativistic neutron star merger simulations, using Radice's high-precision GR hydrodynamics code WhiskyTHC within the Einstein Toolkit simulation framework. The focus of this study was on generating high-fidelity waveforms from the inspiral phase (we simulated for about 10 orbits with 4 different resolutions) of equal mass double neutron star systems and to study the non-axisymmetric deformation of the hypermassive neutron star formed after merger. This deformation is dominated by m=2 ("bar'") contributions, but we also found an m=1 "one armed spiral" to be present, leading to gravitational wave emission through the l = 2, m= 1 mode at half the frequency of the dominant l = 2, m = 2 mode. We showed that this m=1 mode appears robustly even in equal mass quasicircular binaries. Previous work at lower numerical order and lower numerical resolution argued that m=1 should be present only in the case of unequal mass binaries and eccentric mergers. Comparing with the high-resolution equal-mass simulations carried out by Kenta Kiuchi of the YITP group, we found that the YITP simulations also contain the $m=1$ mode. This gave us additional confidence in our results.

The postmerger gravitational wave emission carries information on the uncertain equation of state of nuclear matter. However, since the dominant l=2, m=2 postmerger gravitational wave emission occurs at frequencies of 2-4 kHz, second-generation gravitational wave detectors like Advanced LIGO, KAGRA, and Advanced Virgo will have a hard time detecting the postmerger signal. Since the m=1 mode leads to gravitational wave emission at lower frequency, the hope was that it could be detected more easily, revealing the sought-after information on the nuclear equation of state. Unfortunately, our results clearly show that because of its very narrow-band emission, the signal to noise ratio of the $\ell = 2, m=1$ mode is very small. Even if the binary is optimally oriented and in the nearby Virgo cluster of galaxies (D ~ 10 Mpc), it would require third-generation detectors such as the Einstein Telescope to detect the signal.

The resulting paper has been submitted to PRD as Radice et al. 2016b. It is currently under review and available on arXiv as arXiv:1603.05726, http://arxiv.org/abs/1603.05726. It has been assigned YITP report number YITP-16-21.

2.5. Numerical Modeling of the Early Light Curves of Type IIP Supernovae
(with Viktoriya Morozova, Tony Piro, and Mathieu Renzo)

In this project with my postdoc Morozova and collaborators Piro (Carnegie Observatories) and Renzo (Amsterdam), we used our open-source SuperNova Explosion Code (SNEC). We studied the early shock-cooling dominated light curves of Type IIP (P stands for "plateau") supernovae from red supergiant stars (RSGs). SNEC was first presented in Morozova et al. 2015. It is a Lagrangian (working in co-moving coordinates) spherically symmetric Newtonian radiation-hydrodynamics code. It solves photon radiation transport in the equilibrium (gray) diffusion approach to predict the lightcurves of supernova explosions. Starting with a progenitor star model from a stellar evolutionary code, we artificially initiate an explosion at some prescribed mass coordinate, then follow the explosion up to ~100 days after shock breakout.

In this new study, we focused on the light curve in the first ~20 days after shock break out. During this time, the light curve emission comes from the shock heated, cooling and expanding stellar material. At later times, the plateau emission sets in, which is provided by recombination of ionized hydrogen to neutral hydrogen. Focusing on the early light curve, we found that the time between shock breakout and the maximum of the light curve can be used to put constraints on the pre-explosion radius of the RSG progenitor. This is very interesting, (a) since RSG radii are presently very uncertain and very sensitive to the parameters used in stellar evolution codes and (b) because automated astronomical surveys are beginning to provide increasingly detailed observations of IIP supernovae, which can be used together with our numerical models to observationally determine RSG radii with good accuracy.

The resulting paper has been submitted to ApJ as Morozova et al. 2016. It is currently under review and available on arXiv as arXiv:1603.08530, http://arxiv.org/abs/1603.08530. It has been assigned YITP report number YITP-16-32.

2.6. Simulations of Inspiraling and Merging Double Neutron Stars using the Spectral Einstein Code (with Roland Haas and the SXS Collaboration)

The project underlying this paper started in 2009, soon after I had taken up my assistant professorship. At the time, the Caltech-Cornell (SXS) Spectral Einstein Code (SpEC) had just been upgraded to include general-relativistic hydrodynamics with the goal of simulating black hole -- neutron star binary mergers. It seemed obvious to me that the next step should be simulating neutron star -- neutron star
(NSNS) mergers. SpEC is an appealing code for BHNS and NSNS merger simulations, (a) since it treats the the gravitational part in a pseudospectral framework with exponential convergence and extremely high accuracy and (b) because it uses a comoving coordinate system in which the neutron stars are stationary during the inspiral, avoiding any errors due to advection of neutron star material through the grid.

Unfortunately, while it seemed easy at first, simulating NSNS mergers with SpEC turned out much more difficult than thought. These difficulties were caused by numerical problems in the inspiral phase that spoiled convergence with resolution and took years of graduate student and postdoc time to resolve. Furthermore, once the two neutron stars merge, they form a potentially long-lived hypermassive neutron
star remnant that eventually collapses to a black hole. The dynamical formation of a black hole had previously not been attempted with SpEC, so we had to develop the necessary computational technology to dynamical find a newly appearing apparent horizon and then excise the spacetime and matter interior to it from the computational domain.

Real progress on NSNS mergers with SpEC began in 2012, when then postdoc Roland Haas joined our team at Caltech (he has now moved on to Alessandra Buonanno's group at the Albert Einstein Institute). With Roland, we have now completed the longest-ever NSNS inspiral and merger simulation (~22 orbits, ~44 wave cycles). This simulation, along with an extensive discussion of the changes made to SpEC to make it work, are summarized in a paper that will be submitted to PRD before April 5, 2016 as Haas et al. 2016. It is not yet available on arXiv. It has been assigned YITP report number YITP-16-39.

3. 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.

3.1 Black Hole and Accretion Disk Formation in Gamma-Ray Burst Progenitors
(with Kenta Kiuchi, Yuichiro Sekiguchi, and Masaru Shibata)

In the collapsar scenario for long gamma-ray burst, a massive star collapses to a black hole with an accretion disk. Accretion power and black hole spin extraction are then believed to power a relativistic outflow that generates the gamma-ray burst. So far it has been impossible to actually simulate this process self-consistently and from first principles. In this project, we are for the first time attempting to combine numerical relativity with realistic microphysics (equation of state and neutrinos) and study core collapse, long-term accretion, black hole formation, and subsequent accretion disk formation from first principles. Because the time to be simulated is thousands of dynamical times of the system, we carry out collapse and accretion until shortly before black hole formation in Sekiguchi's axisymmetric (2D) code and then map to my 3D code to follow black hole and accretion disk formation. So far, the 2D part is complete and we are working on mapping from 2D to 3D. I expect first interesting results of this study to be available in May 2016.

3.2. Dynamical Fragmentation and Stellar-Mass Black Hole Formation in Massive Stars
(with YITP graduate student Joseph Fedrow)

A gamma-ray event was observed in temporal coincidence with Advanced LIGO's gravitational wave event GW150914. Various theorists have proposed scenarios in which a binary black hole coalescence could emit a gamma-ray signal. On model, proposed by Avi Loeb, suggests that a rapidly rotating stellar core could fragment into two pieces during collapse. These then collapse to two black holes, inspiral, and merge. Woosley has generated a precollapse stellar model that could have sufficient angular momentum to allow dynamical fragmentation (but he did not include the centrifugal acceleration in his stellar evolution calculations).

My group has previously studied (Reisswig, Ott et al. 2013, PRL 111, 151101) collapse and dynamical fragmentation in the context of supermassive star collapse. In the project with Fedrow, we are re-considering the Reisswig et al. study in the context of stellar-mass objects. First, we are building spherically symmetric initial conditions and give them approximate (“1.5D”) rotation to study their stability properties. We may find already with this simple 1.5D study that the scenario proposed by Loeb is not viable. If we find viable cases, we will simulate them in 3D, using my group's core-collapse simulation package Zelmani, which is based on the Einstein Toolkit. Fedrow has already started using the Einstein Toolkit for binary black hole simulations.

3.3. Stellar-Mass Binary Black Hole Inspirals in a Gaseous Environment
(with Masaru Shibata and, perhaps, Joseph Fedrow)

This project is related to the fragmentation project and aims to study the effects of a gaseous environment (i.e. a stellar environment) on the inspiral dynamics and the resulting gravitational waveform of a binary black hole coalescence. The goal is to determine the threshold ambient density at which the inspiral and merger signal is changed (by dynamical friction and accretion) to such a degree that it would be inconsistent with the observed waveform of GW150914. If this threshold density is below or near the density expected in the core of a massive star, then this would immediately rule out Loeb's dynamical fragmentation model.

We have already started initial short-term inspiral simulations and are presently working out numerical issues caused by adding general-relativistic hydrodynamics to the binary black hole coalescence simulation. I expect first interesting results of this study in May 2016.