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Report on my visit to the Yukawa Institute for Theoretical Physics in 2018

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Abstract. This report summarizes my activities during my 5 months stay as Visiting Professor at the Yukawa Institute for Theoretical Physics. These activities were supported in part by the International Research Unit of Advanced Future Studies, Kyoto University, Japan.

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Personal Note

I would like to extend my gratitude to Professor Kunihito Ioka for his warm hospitality, help and collaboration. I would also like to thank the entire astrophysics group at YITP for many friendly advices, for making my stay in Kyoto enjoyable, and for taking the time to show me around. Finally, I wish to extend a special thank to Yagi-san for her kindness, willingness, and superb administrative support.

1. Presentations

During my stay I delivered two talks. The first one was an opening talk at the workshop "Jet and Shock Breakouts in Cosmic Transients" that was held at YITP on May 14-18, 2018. The workshop, attended by scientists from various institutes in Japan, covered a range of topics related to shocks and their roles in various high-energy astrophysical systems. The second talk was titled "extreme cosmic phenomena", and was intended for a general audience as part of an Advanced Future Studies seminar at YITP that was held on July 26, 2018.

2. Research Activities

My research encompasses several topics related to High-Energy Astrophysics, including theory of black hole engines, formation and dynamics of relativistic outflows, and the physics of radiation mediated shocks and its application to the early emission observed in various types of cosmic explosions. During my stay I started a collaboration with Prof. Kunihito Ioka on non-relativistic shock breakout from stellar winds, I continued a long-term project on radiation mediated shocks in collaboration with Dr. Hirotaka Ito from the Big Bang Laboratory at RIKEN, who made a special visit to YITP during my stay, and I started a new collaboration on the activation of black hole magnetospheres with Dr. Shota Kisaka upon his visit to YITP. In addition, I completed a numerical study, with my PhD student and another colleague (E. Nakar), on AGN wind feedback in young galaxies (a paper describing this work was submitted for publication in MNRAS). In the following I describe in some greater detail the projects that were at the main focus of my activity during my stay at YITP.

2.1 Radiation Mediated Shocks in Cosmic Explosions

Radiation mediated shocks (RMS) play a key role in a variety of extreme astrophysical systems. They dictate the early emission observed in different types of cosmic explosions, contribute the underlying prompt photospheric emission inferred in gamma-ray bursts, and are responsible for the gamma-ray flash that accompanied the gravitational wave signal in neutron star mergers, like the recent GW170817 event. The prompt electromagnetic signal emitted upon the breakout of a RMS, which depends solely on the shock structure, carries a wealth of information regarding the properties of the system, e.g., the explosion mechanism and progenitor type in supernovae and low luminosity GRBs, the nature of the segregated outflow in neutron star mergers, etc.

In the last decade I devoted much time and efforts to study the properties of RMS, and to develop, in collaboration with H. Ito at RIKEN, a numerical tool that can be exploited to perform detailed Monte-Carlo simulations of RMS under a broad range of conditions. However, the early version of the code was limited to infinite shocks with no photon generation, and so its applicability was restricted to sub-photospheric shocks in gamma-ray bursts under idealized conditions. During the visit of Dr. Ito to YITP, in June 2018, we modified the code to include photon generation and escape, that enable computations of the shock breakout signal in a broader class of objects. As a first project, we performed simulations of RMS with escape in gamma-ray bursts, to study how photon leakage affects the emitted spectrum. Our preliminary results indicate that, in contrast to common believe, the emitted spectrum is non-thermal and quite broad, owing to bulk Comptonization. The results will be reported in a paper currently in preparation.

A second project, presently at the focus of our Monte-Carlo studies, deals with the applications to the breakout of a mildly relativistic RMS from stellar winds, as well as from the ejecta in neutron star mergers - a regime that has not been explored before. These computations will be performed with the new version of the code that includes photon generation and losses. Testing of the modified code started during Dr. Ito's visit to YITP and is in final stages. Some preliminary results have also been obtained.

The numerical simulations of non-relativistic shock breakout in supernovae can be checked in the diffusion regime using analytic approach. This is important both, as a check on the numerical results and to gain further insight into the underlying processes that govern shock emission. In collaboration with Prof. K. Ioka, we developed analytic model of a quasi-steady shock with photon escape, treating the transfer of radiation through the shock in the diffusion limit. Our preliminary results indicate a possible reduction in downstream temperature during the breakout phase, when radiative losses become substantial. This should affect the observed spectrum in ways yet to be explored. A paper describing the method and results is in preparation. The analytic solutions will be compared with the numerical results once the adjustment of the Monte-Carlo code to this regime is completed.

2.2 Activation of Black Hole Magnetospheres

Highly collimated, relativistic outflows are ubiquitous in high-energy astrophysics. They are observed on stellar as well as on galactic scales, and they appear to be the sources of the gamma-ray emission detected in compact astrophysical systems, and potentially also of cosmic rays and high-energy neutrinos. Their formation and acceleration is a long-standing issue in high-energy astrophysics. The leading model is based on the so-called Blandford-Znajek (BZ) mechanism, in which energy is extracted magnetically from a Kerr black hole and transferred to large distances in the form of Poynting flux, before being converted to kinetic energy and radiation. The activation of BZ outflows requires continuous injection of plasma in the magnetospheric region enclosed between the inner and outer light cylinders, the origin of which is yet an open issue. It has been shown that under conditions likely to prevail in many stellar and supermassive BH systems, direct plasma injection may be insufficient to completely screen out the magnetosphere, leading to formation of spark gaps. These gaps are potential sources of TeV emission that can be detected by upcoming observatories. To study the dynamics and emission of such gaps, we (with Benoit Cerutti from IPAG) constructed, for the first time, a fully GR, 1D particle-in-cell code that implements Monte-Carlo methods to compute the interaction of pairs and gamma-rays with the soft photons emitted by the accretion flow. In a preliminary study we computed the dynamics and emission of a gap in a typical supermassive BH for a given input disk spectrum. With Dr. Shota Kisaka, who got involved in this project, we are now exploring a broader parameter regime, that encompasses stellar mass BHs, as well as different disk emission spectra. This work has started at YITP and is currently in progress.

3. Summary

During my stay I had the opportunity to interact with the astrophysics group at YITP, and to start two new collaborations: one with Prof. Kunihito Ioka on shock breakout from a stellar wind, and another one on the activation of black hole magnetospheres with Dr. Shota Kisaka. I also continued a long-term collaboration with Dr. Hirotaka Ito from the BBL in RIKEN, who also visited YITP during my stay, on Monte-Carlo simulations of radiation mediated shocks. My visit to YITP deepened my contacts with the astrophysics community in Japan, and I hope that the new collaborations I started will bear fruits in the very near future.