The Pennsylvania State University
The Graduate School

NEUTRINO AND ELECTROMAGNETIC COUNTERPARTS OF GALAXY AND ASTROPHYSICAL BLACK HOLE MERGERS

A Dissertation in
Physics
by
Chengchao Yuan

Submitted in Partial Fulfillment
of the Requirements
for the Degree of

Doctor of Philosophy

August 2022

The dissertation of Chengchao Yuan was reviewed and approved by the following:

Peter Mészáros
Eberly Chair Professor Emeritus, Astronomy & Astrophysics and Physics
Director Emeritus, Center for Multimessenger Astrophysics
Dissertation Co-Advisor
Chair of Committee

Kohta Murase
Associate Professor of Physics and Astronomy & Astrophysics
Dissertation Advisor

Miguel Alejandro Mostafá
Professor of Physics and Astronomy & Astrophysics
Associate Dean for Research and Innovation

Douglas Cowen
Professor of Physics

Donghui Jeong
Associate Professor of Astronomy & Astrophysics

Nitin Samarth
Professor of Physics
George A. and Margaret M. Downsbrough Department Head

Abstract

The historical coincident detection of gravitational waves (GWs) and electromagnetic (EM) counterparts from the binary neutron star merger event GW 170817 heralds a new era in multi-messenger astronomy. At the same time, since the first discovery of the high-energy astrophysical neutrinos in 2012 by IceCube, neutrino astrophysics has made significant progress and has started playing an increasingly important role in multi-messenger analyses. We are currently in the stage where we can probe the nature of the extreme astrophysical phenomena with the synergies between EM photons, neutrinos, GWs, and cosmic rays.

In this dissertation, I start with an overview of the development of multi-messenger astrophysics and its application to astrophysical mergers. I will present our work on the cumulative diffuse neutrino background from galaxy/cluster mergers and show that our scenario can explain the diffuse neutrino flux without violating the extragalactic γ-ray background constraints (chapter 2). We further demonstrate that the synchrotron and inverse Compton emissions produced by secondary electrons/positrons are consistent with the radio and X-ray observations of merging galaxies such as NGC 660 and NGC 3256 (chapter 3). In chapters 4 & 5, we focus on the jet-induced neutrino and EM counterparts from supermassive black hole (SMBH) mergers subsequent to GW radiation and discuss the detection perspectives for the ongoing and next-generation neutrino, optical, and GW missions. The short γ-ray bursts, which are generally thought to arise from compact binary object (CBO) mergers, could be promising candidates for multi-messenger studies. We then consider a special scenario where short GRBs are embedded in disks of active galactic nuclei (AGN) and investigate their GeV signatures in chapter 6.

In a separate effort, we study the stacking and multiplet constraints on the blazar contribution to the cumulative diffuse neutrino flux, assuming a generic relationship between neutrino and γ-ray luminosities (chapter 7). We show that these two limits are complementary, and our results support the argument that blazars are disfavored as the dominant sources of the 100-TeV neutrino background. This work provides rather general and stringent constraints for future studies of blazar neutrinos.

Table of Contents

List of Figures

List of Tables

Acknowledgments

I would first of all like to express my deep gratitude to my mentor, Dr. Peter Mészáros. In 2015, Peter invited me to visit Penn State as an undergraduate intern working in the high-energy astrophysics group. It was the first time I got a glimpse of neutrino astrophysics. Since then, I embarked on an adventure pursuing the tracks of these elusive but attracting particles lurking in the universe. I always found Peter's guidance and support in every progress I made during this journey. I learned a great deal from him through numerous discussions. He is always there to help whenever I encounter obstacles in a research project, from theoretical calculations to paper writing to scientific presentations and more. His kindness, patience, and expertise in high-energy astrophysics (and beyond) have constantly encouraged me to be a better scientist and a better person.

I am also very grateful to my advisor, Dr. Kohta Murase. His enthusiasm and diligence for science have greatly motivated me throughout my graduate study. I remember many times we discussed the technical problems over email until midnight. He can always provide insightful ideas and suggestions for my work. With his great help, I was able to convert an initial idea into a journal article with a high degree of completeness. His careful, rigorous, and responsible working attitude also inspired me to pursue perfection in my research.

Over the past few years, I have enjoyed working and exchanging ideas with many talented peers, postdocs, and professors. I would like to thank Dr. Donghui Jeong, Dr. Shigeo S. Kimura, Dr. B. Theodore Zhang, Dr. Dafne Guetta, Dr. Imre Bartos, Dr. Asaf Pe'er, Dr. Nicholas Senno, Dr. Ali Kheirandish, Dr. Marco Ajello, Dr. Nick Rodd, Dr. Zsuzsa Márka, Dr. Szabolcs Márka, Ph.D. candidate Jose Carpio, and Ph.D. candidate Yu Jiang. I gratefully acknowledge my dissertation committee: Dr. Miguel Mostafá, Dr. Douglas Cowen, and Dr. Donghui Jeong, for their helpful comments and suggestions on my road to a Ph.D.

Finally, I would like to express my deep gratitude to my family for their endless and unconditional love, help, and support. I also would like to express my loving thanks to my partner, Yijia Li, for being part of my life. It is a pleasure to thank my friends at Penn State, Zhaowei Zhang, Jiayin Dong, Zhao Guo, and Matthias Yang He, for the wonderful times we shared, especially the Friday night dinners and board games. In addition, I would like to thank Jiali Lu, Yifan Zhao, Run Xiao, Tongzhou Zhao, Guang Yang, Monong Yu, Ding Ding, Songyang Pu, Yicheng Zhang, Ningxiao Zhang, and many others, who made my life at State College memorable.

The work presented in this dissertation is supported by NASA under the Grant No. NNX13AH50G, by the Alfred P. Sloan Foundation and NSF grant No. PHY-1620777, No. AST-1517363, No. AST-2108466, No. AST-2108467, No. PHY-1911796, No. PHY-2110060, and No. AST-1908689, by the JSPS Research Fellowship and KAKENHI No. 20H01901, No. 20H05852, and No. 19J00198, by the Eberly Foundation and the IGC Fellowship, and by the European Research Council via ERC consolidating grant 773062 (acronym O.M.J.). The findings and conclusions do not necessarily reflect the view of the funding agencies.