Research Center for the Early Universe
Graduate School of Science
University of Tokyo

Annual Report
2020

令和2年度 年次研究報告

東京大学大学院理学系研究科附属
ビッグバン宇宙国際研究センター
Preface

I am pleased to deliver the annual report of Research Center for the Early Universe (RESCEU) for the fiscal year of 2020 (from April 2020 to March 2021).

RESCEU was founded in 1999 as an institute belonging to Faculty of Science, the University of Tokyo, led by the first director, Prof. Katsuhiko Sato of Physics Department. In 2015 we reorganized the research projects in RESCEU, and now we have three major projects including (1) Evolution of the universe and cosmic structures (led by Prof. Jun’ichi Yokoyama), (2) Gravitational-wave astrophysics and experimental gravity (led by Prof. Kipp Cannon), and (3) Formation and characterization of planetary systems (led by myself). Those projects have been supported by a variety of collaboration among our research affiliates in Departments of Physics, Astronomy, and Earth and Planetary Sciences of Faculty of Science, the University of Tokyo.

Due to the pandemic outbreak of COVID-19, the activity in RESCEU has been seriously affected. We were not able to organize any international meeting nor symposium this year. We had the summer school, but it is entirely online without inviting foreign researchers. Since the official members of RESCEU are mostly working on theoretical projects, however, weekly seminars and regular discussions have been carried out via zoom fortunately.

Finally we are pleased to announce the awards for our RESCEU members. Prof. Jun’ichi Yokoyama received the Commendation for Science and Technology by the Minister of Education, Culture, Sports, Science and Technology in April 2020. Dr. Masamune Oguri received the PASJ Excellent Paper Award in 2020 as a coauthor of Hikage et al. PASJ 71(2019) id. 43, and Dr. Kazuhiro Kanagawa received the PASJ Excellent Paper Award in 2020 as the first author of Kanagawa et al. PASJ 68(2016) id. 43, in March 2021.

We would like to congratulate all of them for their wonderful achievements.

May 2021

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11.2 業績リスト
I

Reports on overall activities at RESCEU in 2020
1 Members

RESCEU members

Yasushi Suto [須藤靖] Director
Jun’ichi Yokoyama [横山順一] Professor
Kipp Cannon Professor
Toshikazu Shigeyama [茂山俊和] Professor
Kenta Hotokezaka [仏岡健太] Associate Professor
Masamune Oguri [大槻真宣] Assistant Professor
Kazumi Kashiyama [樫山和己] Assistant Professor
Kohei Kamada [鎌田耕平] Assistant Professor
Atsushi Nishizawa [西澤篤志] Assistant Professor
Yuu Niino [新納悠] Project Assistant Professor (RESCEU & JSPS Grant of Prof. Shigeyama)
Kotaro Fujisawa [藤澤幸太郎] Project Assistant Professor (RESCEU)
Haruki Nishino [西野玄記] Project Assistant Professor (RESCEU & JSPS Grant of Prof. Kusaka)
Yuji Chinone [茅根裕司] Project Assistant Professor (RESCEU & JSPS Grant of Prof. Kusaka)
Koh Ueno [上野昂] Postdoctoral Fellow (JSPS Grant of Prof. Cannon)
Kazuhiro Kanagawa [金川和弘] Postdoctoral Fellow (RESCEU) (~ 2021/01/31)
Yusuke Yamada [山田悠介] Postdoctoral Fellow (JSPS Fellow)
Tatsuya Matsumoto [松本達矢] Postdoctoral Fellow (JSPS Fellow)
Keisuke Inomata [猪又敬介] Postdoctoral Fellow (JSPS Grant of Prof. Yokoyama) (~ 2020/08/31)
Heather Fong Research Fellow (JSPS Fellow)
Sayuri Nagano [永野早百合] Secretary
Chiyo Ueda [上田千代] Secretary
Reiko Sugiyama [杉山礼子] Secretary
RESCEU affiliates

Naoki Yoshida [吉田直紀]  Professor, Dept. of Physics
Tomonori Totani [戸谷友則]  Professor, Dept. of Astronomy
Kotaro Kohno [河野孝太郎]  Professor, Institute of Astronomy
Mamoru Doi [土居守]  Professor, Institute of Astronomy
Motohide Tamura [田村元秀]  Professor, Dept. of Astronomy
Seiji Sugita [杉田精司]  Professor, Dept. of Earth and Planetary Science
Eiichi Tajika [田近英一]  Professor, Dept. of Earth and Planetary Science
Satoshi Yamamoto [山本智]  Professor, Dept. of Physics
Hideo Higuchi [樋口秀男]  Professor, Dept. of Physics
Chikara Furusawa [古澤力]  Professor, Universal Biology Institute
Aya Bamba [馬場彩]  Associate Professor, Dept. of Physics
Akito Kusaka [日下曉人]  Associate Professor, Dept. of Physics
Kazuhiro Shimasaku [嶋作一大]  Associate Professor, Dept. of Astronomy
Masaki Ando [安東正樹]  Associate Professor, Dept. of Physics
Masahiro Ikoma [生駒大洋]  Associate Professor, Dept. of Earth and Planetary Science
Hajime Kawahara [河原剛]  Assistant Professor, Dept. of Earth and Planetary Science
# 2 Projects

## Project 1. Evolution of the universe and cosmic structures

<table>
<thead>
<tr>
<th>Name</th>
<th>Research theme</th>
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</thead>
<tbody>
<tr>
<td>Jun’ichi Yokoyama</td>
<td>Physics of the Early Universe</td>
</tr>
<tr>
<td>Toshikazu Shigeyama</td>
<td>Coevolution of galaxies and stars</td>
</tr>
<tr>
<td>Naoki Yoshida</td>
<td>Evolution of compact objects and time domain astronomy</td>
</tr>
<tr>
<td>Tomonori Totani</td>
<td>Evolution of the universe probed by gamma-ray bursts and fast radio bursts</td>
</tr>
<tr>
<td>Kotaro Kohno</td>
<td>Dust-enshrouded growth of galaxies and supermassive blackholes</td>
</tr>
<tr>
<td>Aya Bamba</td>
<td>Chemical evolution of the universe with supernova remnant study</td>
</tr>
<tr>
<td>Kazuhiro Shimasaku</td>
<td>Galaxy Formation and Evolution</td>
</tr>
<tr>
<td>Akito Kusaka</td>
<td>Observational cosmology using cosmic microwave background</td>
</tr>
<tr>
<td>Masamune Oguri</td>
<td>Unveiling the nature of dark matter and dark energy</td>
</tr>
<tr>
<td>Kazumi Kashiyama</td>
<td>Evolution of compact objects and time domain astronomy</td>
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<tr>
<td>Kohei Kamada</td>
<td>Particle cosmology</td>
</tr>
</tbody>
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## Project 2. Gravitational-wave astrophysics and experimental gravity

<table>
<thead>
<tr>
<th>Name</th>
<th>Research theme</th>
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</thead>
<tbody>
<tr>
<td>Kipp Cannon</td>
<td>Detection and interpretation of gravitational waves emitted by the collisions of compact objects</td>
</tr>
<tr>
<td>Kenta Hotokezaka</td>
<td>Multi-messenger astrophysics of compact binary mergers</td>
</tr>
<tr>
<td>Mamoru Doi</td>
<td>Identifications of gravitational-wave sources by wide-field and multi-color optical observations</td>
</tr>
<tr>
<td>Masaki Ando</td>
<td>Gravitational-Wave Experiment and Astrophysics</td>
</tr>
</tbody>
</table>

## Project 3. Formation and characterization of planetary systems

<table>
<thead>
<tr>
<th>Name</th>
<th>Research theme</th>
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</thead>
<tbody>
<tr>
<td>Yasushi Suto</td>
<td>Dynamical evolution of orbit and angular momentum of exoplanetary systems</td>
</tr>
<tr>
<td>Motohide Tamura</td>
<td>Exoplanet observations and instrumentations</td>
</tr>
<tr>
<td>Seiji Sugita</td>
<td>An asteroid sample-return mission and feasibility study for an exoplanet observation satellite</td>
</tr>
<tr>
<td>Satoshi Yamamoto</td>
<td>Physics and chemistry of protoplanetary disk formation</td>
</tr>
<tr>
<td>Eiichi Tajika</td>
<td>Diversity and evolution of habitable planets</td>
</tr>
<tr>
<td>Masahiro Ikoma</td>
<td>Diversity and origins of exoplanetary atmospheres</td>
</tr>
<tr>
<td>Hajime Kawahara</td>
<td>Exploring instrumentation and methods for characterizing exoplanets</td>
</tr>
<tr>
<td>Hideo Higuchi</td>
<td>Universal model on motor proteins</td>
</tr>
<tr>
<td>Chikara Furusawa</td>
<td>Evolutionary dynamics of computational cell models</td>
</tr>
</tbody>
</table>
## Symposia and Meetings

**Planet² / RESCEU Summer School**

**Place:** Online  
**Time:** 2020/8/17 (Mon) – 2020/8/19 (Wed)

### Program

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<tr>
<th>Date</th>
<th>Time</th>
<th>Session</th>
<th>Speaker</th>
<th>Title</th>
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</thead>
<tbody>
<tr>
<td><strong>8/17 (Mon) morning</strong></td>
<td>10:00–10:10</td>
<td></td>
<td>Yasushi Suto</td>
<td>Opening remark</td>
</tr>
<tr>
<td></td>
<td>10:10–11:30</td>
<td>(L) Nobunari Kashikawa</td>
<td>High-z galaxies and their environment</td>
<td></td>
</tr>
<tr>
<td></td>
<td>11:30–11:45</td>
<td>Yuta Tarumi</td>
<td>s-process enrichment and the origin of barium in ultrafaint dwarf galaxies</td>
<td></td>
</tr>
<tr>
<td></td>
<td>11:45–12:00</td>
<td>Kana Moriwaki</td>
<td>Component extraction from line intensity maps with conditional GAN</td>
<td></td>
</tr>
<tr>
<td></td>
<td>12:00–12:15</td>
<td>Hyunbae Park</td>
<td>Scatter in the reionization history by baryon-dark matter streaming velocity</td>
<td></td>
</tr>
<tr>
<td><strong>8/17 (Mon) afternoon</strong></td>
<td>13:15–14:35</td>
<td>(L) Hajime Kawahara</td>
<td>Frontier in Exoplanet Characterization</td>
<td></td>
</tr>
<tr>
<td></td>
<td>14:35–14:50</td>
<td>Ayano Komaki</td>
<td>Photoevaporation from protoplanetary disk: dependence on central star spectrum</td>
<td></td>
</tr>
<tr>
<td></td>
<td>14:50–15:05</td>
<td>Shijie Wang</td>
<td>Evolution of the multiplanetary systems deduced from six ALMA disks</td>
<td></td>
</tr>
<tr>
<td></td>
<td>15:05–15:20</td>
<td>Hiroto Mitani</td>
<td>Effect of Stellar Wind on Atmospheric Escape</td>
<td></td>
</tr>
<tr>
<td><strong>8/18 (Tue) morning</strong></td>
<td>10:00–10:40</td>
<td>(T) Seiji Sugita</td>
<td>Topical talk: The Evolution of Ryugu and the Early Solar System Revealed by Hayabusa2 Observations</td>
<td></td>
</tr>
<tr>
<td></td>
<td>10:40–10:55</td>
<td>Daichi Tsuna</td>
<td>Transients upon Black Holes Born From Erupting Massive Stars</td>
<td></td>
</tr>
<tr>
<td></td>
<td>10:55–11:10</td>
<td>Kojiro Kawana</td>
<td>A variety of emission from tidal disruption events of a white dwarf by a black hole</td>
<td></td>
</tr>
<tr>
<td></td>
<td>11:10–11:25</td>
<td>Toshinori Hayashi</td>
<td>A strategy to search for an inner binary black hole from the motion of the tertiary companion: radial-velocity modulations of a star and time-delay effects of a pulsar</td>
<td></td>
</tr>
<tr>
<td></td>
<td>11:25–11:40</td>
<td>Tilman Hartwig</td>
<td>Neural Networks can learn periodic data</td>
<td></td>
</tr>
<tr>
<td></td>
<td>11:40–11:55</td>
<td>Kipp Cannon</td>
<td>Data Analysis in COVID Days</td>
<td></td>
</tr>
</tbody>
</table>
8/18 (Tue) afternoon

13:00–13:40 (T) Tomonori Totani
Emergence of life in an inflationary universe

13:40–13:55 Yici Zhong
How much supernova fall-back can invade newborn pulsar wind and magnetosphere?

13:55–14:10 Naoto Kuriyama
The features of multiple mass eruptions from progenitors of Type IIb supernovae

14:10–14:25 Yuki Takei
A two-temperature radiative transfer simulation for interaction-powered supernovae

14:25–14:40 Lin Haoxiang
Radio afterglow from Fast Radio Bursts produced by Neutron Star Mergers

14:40–14:55 Minori Shikauchi
On the use of CHIME to Detect Long-Duration Radio Transients from Neutron Star Mergers

8/19 (Wed) morning

10:00–11:20 (L) Masaki Ando
Observation of Gravitational-Wave in Space

11:20–12:00 (T) Mamoru Doi
The Tomo-e Gozen Camera the first wide-field CMOS imager

8/19 (Wed afternoon)

13:00–13:15 Leo Tsukada
Stochastic background from ultralight vectors

13:15–13:30 Takuya Tsutsui
Early warning of third generation gravitational wave detector for precessed compact binary merger

13:30–13:45 Keisuke Inomata
Scalar perturbations induced by scalar perturbations

13:45–14:00 Fumio Uchida
A baryogenesis scenario from helical magnetic fields and constraints on it

14:00–14:15 Minxi He
Tachyonic preheating in the mixed Higgs-$R^2$ model

14:15–14:25 break

14:25–14:40 Soichiro Hashiba
Particle production induced by vacuum decay in real time formalism

14:40–14:55 Jun’ya Kume
Quantum correction in gravitational leptogenesis and its renormalization

14:55–15:10 Koki Tokeshi
PBH mass spectrum and window function dependence

15:10–15:25 Takumi Hayashi
Towards Coleman-de Luccia bubble nucleation in the Lorentzian path integral

15:25–15:30 Jun’ichi Yokoyama
closing

(L: Lecture, T: Topical talk)
4 RESCEU colloquia

- RESCEU Colloquium No. 45
  Gilles Ferrand (Astrophysical Big Bang Laboratory (ABBL), Cluster for Pioneering Research, and Interdisciplinary Theoretical and Mathematical Sciences Program (iTHEMS), RIKEN)
  “From the thermonuclear supernova to the supernova remnant”
  November 26, 2020, 10:30-11:30

- RESCEU Colloquium No. 46
  Akira Endo (Delft University of Technology, on behalf of the DESHIMA collaboration)
  “DESHIMA: Integrated Superconducting Spectrometer for Wideband Submillimeter Astronomy”
  December 10, 2020, 17:00-18:00

- RESCEU Colloquium No. 47
  Takaaki Tanaka (Kyoto University)
  “Recent X-ray Studies of Supernova Remnants and Beyond”
  February 18, 2021, 14:00-15:00

- RESCEU Colloquium No. 48
  Hiroki Akamatsu (SRON Netherlands Institute for Space Research)
  “Energetics of galaxy clusters and cryogenic probes for future astronomical applications”
  March 25, 2021, 16:00-17:00
II

Reports on the research activities of each project in 2020
5 Project 1. Evolution of the universe and cosmic structures

5.1 Activity Report

This project aims at clarifying the origin and evolution of both matters and structures of the Universe based on theoretical and observational studies. It covers physics of the early universe including but not limited to inflation, cosmological phase transition, formation and evolution of density perturbation, as well as formation and evolution of the hierarchical structure of the universe, namely, stars, galaxies, and clusters of galaxies in terms of numerical simulations and optical and X-ray observations. Cosmic microwave background radiation and gravitational waves are also important probe of the Universe and are actively investigated in this project. These studies not only clarifies the evolution of our Universe but also provide us with invaluable informations on the nature of dark matter and dark energy. Below are highlights of the achievements in FY2020 listed in descending scales.

5.1.1 Inflationary cosmology

We studied the realization of the hot Big Bang Universe after inflation, namely, the reheating, in the mixed Higgs-$R^2$ model. We identified the realization condition of the reported violent particle production mechanism just after inflation, which may lead to quick connection to the hot Big Bang Universe in that model. (Yokoyama, Kamada)

5.1.2 Quantum anomaly in the early Universe

There can be interesting phenomena in the early Universe induced by background magnetic fields as well as gravitational waves through the chiral anomaly inherent in the quantum theories. It causes the Chern-Simons coupling between the pseudo-scalar and gauge fields or gravitational fields. We studied the magnetic field and gravitational wave production from the dynamics of pseudo-scalar fields through the Chern-Simons coupling, that are identified as inflaton and also the phase of the flat direction in supersymmetric theories, which can result in the generation of matter and antimatter asymmetry of the Universe. Especially we clarified the subtleties in the renormalization of the gravitational wave production. We also studied the baryon isocurvature perturbation generated by the primordial magnetic fields generated at the electroweak symmetry breaking. We found that the intergalactic magnetic fields suggested by the blazar observation cannot be explained by the primordial magnetic fields generated before the electroweak symmetry breaking due to too large isocurvature perturbation. (Kamada)

5.1.3 Statistical Computational Cosmology

We applied a sparsity-based method called adaptive LASSO to reconstruct three-dimensional density distribution in the Universe by gravitational lensing observations. We apply an adaptive LASSO algorithm to perform reconstruction on the assumption that the underlying cosmic density field is represented by a sum of Navarro-Frenk-White halos. We generate realistic mock galaxy shape catalogues by considering the shear distortions from isolated halos for the configurations matched to Subaru Hyper Suprime-Cam Survey with its photometric redshift estimates. Galaxy clusters with mass greater than $10^{14}$ solar-masses can be detected with $1.5-\sigma$ confidence, with an average false detection rate of 0.022 per square-degree. The
standard deviation of the redshift estimation is less than 0.1. Our method enables direct three-dimensional cluster detection with accurate redshift estimates. (Yoshida)

5.1.4 Observational cosmology using cosmic microwave background

We conduct cosmology research by observing Cosmic Microwave Background (CMB) through observational projects: Polarbear, Simons Array, and Simons Observatory.

The Polarbear experiment and its successor, Simons Array, are designed to measure both inflationary signature and the gravitational lensing effect in CMB polarization. Polarbear has concluded its observation campaign in 2016, and our focus has been on data analysis. Our recent results from this project include the first demonstration of so-called “de-lensing,” a rejection of contamination due to gravitational lensing effect in reconstructing primordial B-mode power spectrum, using CMB polarization data only. We also released several results influential to future CMB projects, including: 1) improved measurement of the gravitational lensing power spectrum measurement, 2) constraint on the tensor-to-scalar ratio \( r \), and 3) the E-mode power spectrum and constraint on the cosmological parameters.

For Simons Array experiment, observation using the first telescope and the deployment of the second telescope were paused due to COVID-19 pandemic; we virtually lost our access to the telescope site in Chile. We managed to gain access to the site toward the end of 2020, and resumed observation at the beginning of 2021 using the first telescope. The deployment of the second telescope is underway toward the first light soon. In parallel, development of the analysis pipeline is actively on-going.

The Simons Observatory experiment is scheduled for the first light in 2022 and 2023. We will deploy three 0.4-m Small Aperture Telescopes (SATs), which are dedicated for exploring inflationary signature, and a 6-m Large Aperture Telescope (LAT), which will measure (or constrain) the sum of neutrino masses, and the dark content of the universe. We have primarily focused on the development of SATs, and delivered the cryogenic optics tube for the first telescope. We also made significant progress in fabricating and commissioning the second and third cryogenic half-wave plate rotation mechanism.

We also focus on developing techniques for high-performance computation (HPC) enabling data analysis for Simons Observatory as well as Simons Array, producing order-of-magnitude larger data volume than the previous instruments. While improving computational throughput, we need to improve on the analysis systematics as well. One of our emphasis has been to reduce systematic leakage from the E-modes to B-modes, developing technique to achieve this in a computationally feasible manner. In doing so, we achieved significant improvement in computation time by taking advantage of GPUs. (Kusaka, Kiuchi, Chinone, Nishino)

5.1.5 Probing Dark Matter with Gravitational Waves

We studied the possibility of using amplitude and phase fluctuations of gravitational waves due to gravitational lensing as a probe of the small-scale matter power spectrum, which contains a wealth of information about the particle nature of dark matter. We showed that the frequency dependence of amplitude and phase fluctuations arise from the wave optics nature of the propagation of gravitational waves. It is predicted that gravitational lensing dispersions of gravitational waves at frequencies of \( f \sim 0.1 \) Hz probes the abundance of low-mass dark halos with mass \( 1h^{-1}M_{\odot} \lesssim M \lesssim 10^{4}h^{-1}M_{\odot} \) and hence serve as a new test of the cold dark matter paradigm. We pointed out that primordial black holes (PBHs) with \( M_{\text{PBH}} \gtrsim 0.1 M_{\odot} \) can significantly enhance the signal mainly due to their shot noise. The abundance of PBHs can be efficiently probed with gravitational waves at frequencies of \( f \sim 10 - 100 \) Hz where the enhancement of the signals is large. (Oguri)

5.1.6 ALMA lensing cluster survey: uncovering and characterising highly magnified dust-enshrouded galaxies behind lensing clusters

Recent ALMA observations have unveiled the presence of faint (i.e., sub-mJy at \( \lambda \sim 1 \) mm, significantly fainter than the “classical” bright submillimeter galaxies), dusty star-forming galaxies, which are often invisible in the deepest near-infrared images taken with the HST and 8-m-class telescopes. They seem to
represent the bulk population of massive galaxies at $z > 3 - 4$ and beyond, which have been completely missed by the Lyman-break galaxy selection using HST/WFC3. Due to its faintness, however, detailed physical characterization of the faint dusty star-forming population remains a challenge; even using ALMA, spectroscopic follow-up studies of these faint galaxies can be very expensive. With these backgrounds, we have conducted the ALMA lensing cluster survey (ACLS, PI: K. Kohno. co-PIs: M. Oguri et al.), a 96-hour ALMA large program in cycle-6. It aims at obtaining high-resolution (~arcsec) 1.2-mm images of high-magnification regions of 33 lensing clusters with a depth of $\sim 70 \mu$Jy ($1\sigma$), covering $\sim 110$ arcmin$^2$ in total. We have two frequency tuning setups, resulting in a total frequency coverage of 15 GHz, which allows us to search for millimeter-wave line emitting galaxies. The sample is taken from the best-studied massive clusters including CLASH, HFF, and RELICS. We have securely detected 129 continuum sources above $5\sigma$, and it will become 113 independent continuum sources even after removing multiple images by cluster lens. We find a significant number of near-infrared-dark, magnified (but intrinsically faint) dusty star-forming galaxies, and follow-up studies of them are on-going. As one of the initial outcomes, we published a discovery of a triple image "H-band-dropout" ALMA galaxy, which is associated with a galaxy group at $z = 4.32 - 4.33$, lensed by the massive galaxy cluster ACT-CL J0102-4915 (aka El Gordo) at $z = 0.87$ (Caputi, K., Caminha, G., Fujimoto, S., Kohno, K., et al. 2021, ApJ, 908, 146). We also uncover a multiply imaged sub-L$^*$ galaxy at $z = 6.072$ behind the massive cluster RXC J0600-2007 at $z = 0.430$ (Fujimoto, S., Oguri, M., Brammer, G., Yoshimura, Y., Laporte, N., Kohno, K., Shimasaku, K., et al., ApJ, 911, 99; Laporte, N., Zitrin, A., Ellis, R. S., Fujimoto, S., Oguri, M., Kohno, K., et al. 2021, MNRAS, in press). It exhibits a surprisingly elevated [CII] 158 $\mu$m emission ($\sim 25$ mJy) because of its high magnification ($\mu \sim 20$ on average). In fact, after careful identification of multiple images and refinement of the mass models led by M. Oguri and our collaborators, we find that this galaxy straddles the caustics at $z = 6.07$ so a part of this galaxy reaches an extremely high magnification up to $\mu \sim 160$ (!). The reconstructed [CII] 158 $\mu$m line, rest-frame far-infrared continuum (i.e., ALMA band-6 or 1.2 mm continuum), and rest-frame ultraviolet (i.e., HST/F160W or near-infrared H-band) images reveal the distributions of stars and interstellar medium at 100 - 300 pc scales. Given the uniqueness of the uncovered galaxy as an intrinsically faint (ergo ubiquitous), sub-L$^*$ galaxy, an intensive follow-up campaign has been launched, including the approved JWST GO-1 program using NIRCam and NIRSpec IFU (PI. Fujimoto, S.). (Kohno, Oguri, Shimasaku)

### 5.1.7 High redshift galaxies

We compare the spatial distribution of LAEs at $\sim 2$ with that of IGM HI gas, a faithful tracer of matter distribution, finding that LAEs tend to be located on the near (to us) sides of HI dense regions because those on the far sides suffer from heavier Ly$\alpha$ absorption. This result indicates that care is needed when using LAEs to search for overdense regions of matter. We search for bright $z = 7.3$ LAEs using deep HSC/NB1010 imaging data, finding no source. We use this result to obtain a lower limit to the HI neutral fraction to be $> 0.28$. This indicates that cosmic reionization is still ongoing at $z = 7.3$. (Shimasaku)

### 5.1.8 Astrophysical transients: their origins and consequences

The following topics were studied in this project.

- Binary neutron star mergers in faint dwarf spheroidal galaxies (Shigeyama)
- Optical emission immediately after binary neutron star mergers (Shigeyama)
- Observations of the early light from type Ia supernovae (Shigeyama; Doi, M.)
- Influence of Pop III supernova explosions on the companion stars (Shigeyama)
- Rapidly rotating massive white dwarfs as a result of binary white dwarf mergers (Kashiyama, Fujisawa, Ko, Shigeyama)
- Emission of type IIn supernovae (Shigeyama, Tsuna, Kashiyama, Takei)
- Eruptive mass loss from a massive star a few years before the core collapse (Shigeyama, Kuriyama)
- Accretion of C+O matter onto a neutron star igniting Carbon burning (Shigeyama, Nagarajan)
5.2 Publication List

- Influence of supernova fallback on newborn neutron star magnetospheres (Shigeyama, Kashiyama, Zhong)
- Rotational equilibria on the 2D Lagrange coordinates (Fujisawa)
- The W4 method: a new multi-dimensional root-finding scheme for nonlinear systems of equations (Fujisawa)

Here the names of researchers are listed in the parentheses.

5.1.9 Probing the origin of compact objects in the universe by theoretical modeling and multi-wavelength observations

We studied radio afterglows from binary neutron star (BNS) mergers, and especially its implications for fast radio bursts (FRBs). If some of FRBs are produced by BNS mergers, radio afterglows may be detected by follow-up radio observations of FRB locations. We made quantitative predictions using a latest afterglow model of BNS mergers. Totani also studied on the origin of the Fermi bubble, which is a giant gamma-ray bubble structure towards the Galactic Center. Structures found in the X-ray and radio diffuse emission in this region were compared in detail, and their origin were discussed. (Totani)

5.1.10 X- and γ-ray study of high-energy astrophysics

Our aim is understanding high energy phenomena in the universe, such as supernova explosions and their remnants, compact stars such as neutron stars and blackholes, and active galactic nucleus. Such high energy objects emit X-rays and gamma-rays, so we observe such high energy photons using balloons and satellites.

This year we examined carefully how and when accelerated particles on the shocks of supernova remnants escape to the space and become galactic cosmic rays. With systematic study of a few tens supernova remnants in X-ray and gamma-ray band, it is found that accelerated particles escape from the acceleration sites (shocks of supernova remnants) within ~10 kyrs. This is the first observational measurement of particle escape from the acceleration sites. The acceleration efficiency has diversity within the order of 3, which means that only a few supernova remnants contribute the Galactic cosmic rays.

Torus of active galactic nucleus (AGNs) feed supermassive blackholes and important to understand the co-evolution of galaxy and the blackholes. This year we have made systematic analysis of AGNs hidden by their torus with the X-ray emission model we developed (“XClumpy”), and found that around half of AGNs are hidden type. It is found that the covering fraction by their torus is larger than previously expected. Our result implies that there are more undiscovered AGNs hidden by their torus.

We also study on the detector development for the near future missions. For the XRISM, to be launched on the Japanese fiscal year 2022, we fixed the performance verification targets. For Cipher mission, the first imaging polarimetry cubesat in the hard X-ray band, we tested the X-ray use of infrared CMOS sensor and found that it totally satisfies our requests with good efficiency. We also started GRAMS mission development in this year. (Bamba)

5.2 Publication List

5.2. PUBLICATION LIST


[38] Fukushima H., Hosokawa T., Chiaki G., Omukai K., Yoshida N., Kuiper R., 2020, MN, 497, 829


5.2. PUBLICATION LIST

[42] KAGRA Collaboration (incl. Kashiyama K.), Progress of Theoretical and Experimental Physics, ptaa120.
5.2. PUBLICATION LIST


5.2. PUBLICATION LIST


[112] Ando, M., Shimasaki, K., Momose, R., “A systematic search for galaxy proto-cluster cores at z ~ 2", 2021, IAUSS, 359, 166


5.3. INTERNATIONAL CONFERENCE TALKS

5.3.1 Contributed talks


[133] Kana Moriwaki, "Component extraction from line intensity maps with conditional GAN", RESCEU Summer School, Online (August 17, 2020)

5.3. INTERNATIONAL CONFERENCE TALKS


[141] Yuji Chinone, “A Null test framework for B-mode measurements with POLARBEAR,” CMB systematics and calibration focus workshop, Kavli IPMU, Kashiwa, Japan, Online (November 2020)


[152] Lin, H., “Afterglows from neutron stars and fast radio bursts”, Connecting high-energy astroparticle physics for origins of cosmic rays and future perspectives (CRPHYS2020), YITP, Kyoto University, Japan, Dec. 7-10, 2020


[156] Mitani H.,“Stellar wind effect on the atmospheric escape of hot Jupiters”, AGU Fall Meeting, Online(December 8, 2020)


5.3. INTERNATIONAL CONFERENCE TALKS


[161] Kana Moriwaki, "[OII] line emitters as a probe of galaxy-21 cm cross-correlation signals from the early stage of reionization", SAZERAC The 21-cm Signal from Cosmic Dawn and the Epoch of Reionization, Online(January 29, 2021)


5.3.2 Invited talks

[168] Yoshida N., "Zooming in onto the origin of heavy elements", First Light Reunion, Online(May 29, 2020)


[175] Kana Moriwaki, ”Deep learning application for line intensity mapping”, The 9th KIAS Workshop on Cosmology and Structure Formation, Seoul(November 3, 2020)


5.3. INTERNATIONAL CONFERENCE TALKS


6 Project 2. Gravitational-wave astrophysics and experimental gravity

6.1 Activity Report

6.1.1 Kipp Cannon group

Our research group studies black holes, neutron stars, exotic astrophysical objects, and the Universe using gravitational waves, and sometimes also electromagnetic observations as well. Gravitational waves are waves of spacetime curvature generated by the movement of mass and momentum. There are many reasons why gravitational waves are an interesting way to explore the sky. Because gravitational waves are generated by physical processes different from those that produce light or radio waves (which are generated by the movement of electric charges and currents), gravitational waves carry different information about their sources than is carried by electromagnetic waves. Gravitational waves interact weakly with matter allowing them to pass through material that would be opaque to radio waves and light. For example we expect that gravitational waves can escape the dense deep cores of supernovae, and show us the earliest moments of the Big Bang. The Earth, too, is transparent to gravitational waves, so gravitational-wave telescopes can see the sky below them through the Earth as easily as they can see the sky above, allowing gravitational-wave telescopes to monitor the whole sky continuously, day and night. Gravitational waves are the only significant form of energy expected to be radiated by some of the most exotic events in the universe like the collisions of black holes. However, because everything is nearly transparent to gravitational waves, it is very difficult to build a device that can detect them, and the first detection of this form of energy was only achieved in 2015.

Our research group’s members are members of the LIGO Scientific Collaboration (LSC) and KAGRA Collaboration, and we analyze data collected by the two LIGO gravitational-wave antennas in the United States, the Virgo antenna in Italy, the GEO600 antenna in Germany, and the KAGRA antenna in Japan. The Advanced LIGO and Advanced Virgo antennas were conducting their third observational data-taking run, “O3”, through the 2019/2020 academic year, and were expected to continue through most of the 2020/2021 academic year, however, due to the pandemic, observations were stopped in late March 2020, and so unfortunately the 2020/2021 academic year saw no new data from the LIGO/Virgo detector network. Members of our group are active in all aspects of observational gravitational-wave astronomy, the following are some highlights from FY2020.

Compact Object Collisions

When heavy stars exhaust their fuel supply they undergo gravitational collapse. The end state of this process can be a neutron star or a black hole. There are many of these in the Universe, and occasionally they collide with one another. These collisions are very powerful sources of gravitational radiation. Since the first detection of gravitational waves from the collision of a pair of black holes in September, 2015, we have been able to study the behaviour of strongly curve spacetime.

This past academic year saw many new discoveries of black hole and neutron star collisions. Two of these are especially noteworthy. The gravitational wave signal GW190521 was the collision of a 23 solar-mass black hole and an object with the unusual mass of about 2.6 solar masses. It’s not clear if the lighter object is a neutron star or black hole, and both options are unusual. If a neutron star, it would be the heaviest neutron star known and above the maximum mass allowed by a number of neutron star equation of state models; if a black hole, it might be the smallest known black hole. The signal was discovered by the GstLAL detection system developed by members of RESCEU. A second remarkable discovery was GW190814, a collision of two black holes with a total mass of 150 solar
masses. Both of the black holes involved in the collision, and certainly the heavier of the two, have masses above the so-called pair production bound. This refers to a process triggering the collapse of a star when its core reaches a certain mass, and because of this process it’s believed that black holes above that mass cannot form during supernovae. These black holes were larger than that limit. They might be the result of earlier collisions of smaller black holes, but in any case their life stories are more complicated than the other black holes we’ve observed.

Other on-going projects within our group include the development of techniques for removing signals from detector data for the purpose of constructing clean noise models, the development of an ultra high-speed sky mapping system suitable for use in early-warning detection systems, and the development of a system to estimate the sensitivity of a search for gravitational waves mathematically, replacing the current computationally costly technique of hiding fake signals in the data and searching for them with the detection software. Group members have contributed to the search for gravitational-wave echoes from gravitational lenses — waves from compact object collisions that arrive at Earth from multiple directions at different times from having followed more than one path through spacetime. Studies of compact object collisions are in some ways limited by the available computer resources, so the more efficiently we can use them the more knowledge we can obtain, and improving analysis efficiency is a theme in our group. One on-going project in this regard is the development of techniques to reduce the enormous data volume of the detection systems to allow intermediate retained and reused for multiple analyses.

Transients from Newborn Black Holes

The origin of the binary black holes detected by the Advanced LIGO and Virgo detectors is one of the biggest problems in gravitational wave astrophysics. One unique pathway to probe this is to directly observe the formation of black holes. With members of other labs in RESCEU, we are conducting theoretical research on transients following black hole formation. When a black hole forms from a massive star, a fraction of the outer envelope is ejected because gravity from the collapsing core decreases due to emission of neutrinos. We calculated months-long electromagnetic emission from this mass ejection, and found that this can explain the enigmatic intermediate luminosity red transients found by recent transient surveys. We have also researched the possibility of observing black hole formation through gravitational waves. A recent re-analysis of the neutron star merger event GW170817 resulted in a tentative detection of a gravitational-wave signal at 1 second post-merger. We have shown that a phenomenon called gravitational wave echoes, inspired by models of quantum gravity, can explain the amplitude and frequency of this signal. We have also shown that these echo signals, if real, can also be caught by future gravitational-wave detectors when massive stars in nearby galaxies collapse to black holes.

Exotica

Cosmic strings are theoretical topological defect structures left over from the cooling process of the early Universe. Although none have been discovered, a broad spectrum of theories of fundamental physics predict their existence. Even if they exist, they might be so rare that none are present in the part of the Universe visible to us. Either way, searching for them and either confirming their existence or putting limits on their number will teach us a great deal about fundamental physics. Members of our group led the development of the LSC and Virgo Collaboration’s cosmic string detection pipeline and are currently analyzing the data collected during the O3 observing run, searching for evidence of these signals using a new analysis system developed by RESCEU members. The new system is more computationally efficient than the previous system, and makes use of more sophisticated statistical analyses allowing it to make a confident detection claim should a signal ever be found in the future. The results of this work were published this past year in June 2021 at Physical Review Letters.

Recently we have begun developing a search for Cherenkov radiation-like bursts of gravitational waves. When an electric charge moves through a medium above the speed of light in that medium it generates an optical shock wave — a flash of light known as Cherenkov radiation. This same phenomenon occurs in acoustic systems as a sonic boom, and as the wake behind boats moving through water above the speed of surface waves. It stands to reason that a gravitational charge (a mass) moving at superluminal speeds would generate a gravitational wave flash in a similar way. There is some interest in this phenomenon at the microscopic scale as a symptom of non-Lorenze invariance, but at the macroscopic level there is no known source mechanism. Nevertheless, as an educational exercise for students, developing a search for such signals will be a very productive and entertaining activity.
Test of gravity with gravitational-wave polarizations

Many gravity theories that extend the general theory of relativity have been proposed so far, and it is important to verify the correctness of the theory from various aspects with higher accuracy in order to deepen our understanding of gravity. Since the first detection of gravitational waves, it has become possible to investigate the nature of gravity in the vicinity of celestial bodies that emit gravitational waves, that is, in a dynamical and extremely strong gravitational field. One of the ways for verifying gravity in such a situation is the polarization modes of gravitational waves. The number of polarization modes is unique to each gravity theory. There are two tensor modes in general relativity, while three or more polarization modes in extended theories of gravity. In other words, the true gravity theory can be identified by examining the number of polarization modes from the observation data. We analyzed the actual observation data of the gravitational wave detectors and found no signs of polarizations inconsistent with the prediction of general relativity. Therefore, we obtained a new result that supports the correctness of general relativity. In addition, in order to test the theories of gravity, we study cosmological models in the concrete modified gravity theories and classify them based on the observational properties about gravitational waves.

Future Observatories

Overlapping of gravitational-wave signals in the future gravitational-wave detectors

Future terrestrial gravitational wave detectors such as Einstein Telescope and Cosmic Explorer are expected to observe a large number of gravitational wave events (hundreds of thousands of events per year) from binary coalescences of neutron stars and black holes. If the number of events is too large, the gravitational wave signals in the detector data may overlap each other, which may affect the parameter estimation of an individual gravitational wave signal. In the worst case, these signals cannot be separated and make their detections difficult. To study this issue, we first performed a simulation to randomly generate gravitational wave events and estimated how much gravitational wave signals would overlap. Then, it was investigated how much the error of parameter estimation and the estimation bias are degraded when the gravitational wave signals overlap. As a result, it was found that the parameter estimation was hardly affected unless the waveforms of the overlapping gravitational wave signals were very similar. Therefore, our conclusion is that the overlaps of gravitational wave signals can occur frequently but do not cause a problem for parameter estimation in the future gravitational wave detector.

Study on sensitivity improvement for the future gravitational-wave detectors

Currently operating gravitational wave detectors on the ground are LIGO, Virgo, KAGRA and GEO600, which will be upgraded and more sensitive within the next five years. Since the best way of the upgrade depends on technologies available today and their difficulties to realize, the detailed examination is required. We joined the working group on an upgrade of the Japanese detector KAGRA to KAGRA+ and considered the update plan and the sensitivity optimization. Meanwhile, a space gravitational wave detector is also planned for his future in the 2030s. In particular, the DECIGO project, which is being promoted mainly by Japan, aims to detect primordial gravitational waves originating from inflation, and sensitivity improvement and optimization for that purpose are also being studied.

People and Things

One of our Master’s students, Mr. Chi-Wai Chan, defended his thesis and continued in our group as a doctoral student, and one of our doctoral students, Dr. Leo Tsukada, successfully defended his thesis and has secured a research position at Pennsylvania State University, where he will continue his work on searches for stochastic gravitational wave backgrounds and for compact object collisions.
6.1.2 Kenta Hotokezaka group

**Kilonova, r-process, radio counterpart**

Kilonovae are optical-near IR transients associated with binary neutron star mergers and black hole neutron star mergers. In the LIGO/Virgo O3 observing run, the compact binary merger candidates were actively observed in the optical band to find a kilonova. However, no kilonova candidates were found. We highlighted the follow-up campaigns for two neutron star black hole candidates, two binary black hole candidates, and a Mass-Gap binary candidate [1]. We concluded that the follow-up observations are too shallow to catch the canonical kilonova signature.

We studied the turbulent mixing of r-process elements in the interstellar medium [7]. We found that the inhomogeneity of r-process elements inferred from the various measurements such as the chemical abundances of metal poor stars, the geological measurements of short-lived r-process elements supports the neutron star merger scenario of the origin of r-process elements.

We participated in a radio follow-up observations for GW170817 with LOFAR [2]. Unfortunately, no signal was found partly due to the fact that the sky location of GW170817 is not optimal for LOFAR. We also studied the potential that future radio observations can constrain the size of the emission region of the radio counterparts of neutron star mergers [3].

We found that both VLBI measurements and scintillation methods will be powerful to constrain the size and superluminal motion of the merger outflows for events with distance out to $\sim 100$ Mpc.

**Shock Acceleration of neutrinos in core collapse supernovae**

In core collapse supernovae (CCSNe), a huge amount of energy is carried away by neutrinos. Indeed, this picture was confirmed by the direct neutrino observations of SN 1987A. If the next Galactic supernova happens, it is expected that the deep inside of core collapse explosion can be studied in great detail with $10^3$ to $10^4$ neutrinos, c.f., Kamiokande II detected only a dozen of neutrinos.

We studied the neutrino shock acceleration taking place in core-collapse supernova [5]. The leading players here are heavy leptonic neutrinos, $\nu_\mu$ and $\nu_\tau$; the former and latter potentially gain the energy up to 100 and 200 MeV, respectively, through the shock acceleration because they interact with material mainly through scatterings with nucleons and nuclei. By using a Monte Carlo neutrino transport simulation, we showed that the neutrino shock acceleration commonly occurs in the early post-bounce phase ($<50$ ms after bounce) for all massive stellar collapse experiencing nuclear bounce and would reoccur in the late phase ($>100$ ms) for failed CCSNe. This produces a distinctive high energy tail around 100 MeV. We estimated the expected event counts for Hyper(Super)-Kamiokande, DUNE, and JUNO. We found that the event counts with the energy of $>80$ MeV are a few orders of magnitude higher than that of the thermal neutrinos regardless of the detectors, and muon production may also happen in these detectors by $\nu_\mu$ with the energy of $>100$ MeV. Such neutrino signals will provide a precious information on deciphering the inner dynamics of CCSN and placing a constraint on the physics of neutrino oscillation; indeed, the detection of the high energy neutrinos through charged current reaction channels will be a smoking gun evidence of neutrino flavour conversion.

6.2 Activity report of Affiliates

6.2.1 Ando Masaki

The Ando group is working on experimental research for gravitational-wave observations, in particular for large projects such as KAGRA and B-DECIGO. KAGRA is a gravitational-wave antenna at Kamioka, Gifu prefecture in Japan. We have been playing a key role since the conceptual study phase before the start of the project in 2010. The installation of the main components was completed in FY2018, and we are in the commissioning phase; shakedown and tuning for full operation of the interferometer. In FY2020, the KAGRA interferometer started an observation run, named O3GK. Our group members led the commissioning and operation of the interferometer. We are also working on B-DECIGO, which will be a space-borne gravitational wave antenna with observation band around 0.1 Hz. We conducted theoretical studies of science cases for this mission as well as experimental development of critical subsystems, such
as laser interferometer, stabilized laser source, drag-free system, and low-noise thruster. In FY2020, we continued a system design study with a company so as to show the feasibility of the full mission. This activity was financially supported by RESCEU. In addition to these experimental activities, we are also working on theoretical and data-analysis research. The motivation is to test the theory of gravity using polarization information of the observed gravitational-wave signal. We made estimations of test precisions using current and future gravitational-wave antennae.

6.2.2 Doi Mamoru

Two optical instruments are being developed by Doi, Shigeyama and other colleagues, with the goal of studying Kilonovae and other transients.

The first instrument is the Tomo-e Gozen camera (Tomo-e), which is a wide-field optical camera with 84 2k × 1k CMOS sensors on the prime focus of the 1.05 m Kiso Schmidt telescope. The CMOS array enables us to take consecutive images with a rate of 2 frames per second covering an instantaneous field-of-view (FoV) of 20 square degrees. Tomo-e can do very wide (~one thousand square degree) searches for the optical counterpart of a GW source in one hour. Tomo-e can also search for kilonova by itself with wide surveys. In FY2020 we have carried out a mixed wide survey with a single scan of the 7000 deg^2 sky and a frequent survey of a 2000 deg^2 sky area more than 10 times every night with intervals shorter than 1 hour. In FY2020, about 2 PByte 2 fps data were taken, and 100 TByte data were reserved after stacking images by 6 seconds – 9 seconds. The data have been processed with dedicated pipeline software which searches for transients/moving objects using machine learning techniques. More than 20 newly discovered near-Earth objects were found, and many supernovae have been observed so far. There was no Kilonova candidate found, though we are still improving data analysis, and making better reference images taken by Tomo-e itself.

The second instrument is TriCCS, a three band (g,r,i or z) simultaneous imaging spectrograph for a Nasmyth focus of the Seimei 3.8 m telescope. TriCCS is being developed by Doi, Sako, Niino (UTokyo), Maeda, Matsubayashi, Ohta, Kawabata (Kyoto University), and graduate students. TriCCS adopts high sensitivity CMOS sensors by Canon Co., which can take 100 frames per second. The field of view of TriCCS is about 10' × 5', which is not very wide, but color or spectral information can be obtained, taking advantage of the 3.8 m telescope aperture. Hence TriCCS is suitable for deep follow-up observations of kilonova and other transients. Commissioning observations were carried out five times in FY2020, and the basic performance for imaging mode was verified, which will be open to the community in 2021B. Preparation of low-resolution spectroscopy mode was also done.

Simultaneous observations of Fast Radio Bursts were also carried out with Tomo-e and CHIME experiment twice in March 2021. Unfortunately there was no FRB during the observation periods.

6.3 Publication List


[37] KAGRA Collaboration: Application of independent component analysis to the iKAGRA data, PTEP, 053F01 (2020).


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KAGRA Collaboration: Vibration isolation systems for the beam splitter and signal recycling mirrors of the KAGRA gravitational wave detector, Class. Quantum Grav. 38, 065011 (2021).


Takafumi Ushiba et al.: Cryogenic suspension design for a kilometer-scale gravitational-wave detector, Class. Quantum Grav. 38, 085013 (2021).


6.4 International Conference Talks

6.4.1 Contributed talks


N. Aritomi: Frequency Dependent Squeezing with 300 m filter cavity in TAMA, The 25th KAGRA face-to-face meeting (August 2020, Online).


Yuta Michimura for the KAGRA Collaboration: Future Plans for KAGRA Facility, KAGRA-OzGrav Meeting (November 2020, Online).


6.4. INTERNATIONAL CONFERENCE TALKS


6.4.2 Invited talks


7 Project 3. Formation and characterization of planetary systems

7.1 Activity Report

Project 3 “Formation and characterization of planetary systems” approaches the problem both theoretically and observationally through the collaboration with members in Departments of Physics, Astronomy, and Earth and Planetary Sciences. We show several highlights of our research this year.

7.1.1 Radial-velocity variation of a tertiary star orbiting a binary black hole in a triple system

A number of ongoing surveys are likely to discover star-black hole binaries in our Galaxy in the near future. A fraction of them may be triple systems comprising an inner binary, instead of a single black hole, which might be progenitors of binary black holes (BBHs) routinely discovered now from the gravitational wave. We extend our previous proposal to locate inner BBHs from the short-term radial-velocity (RV) variation of a tertiary star in coplanar triples, and we consider noncoplanar triples and their long-term RV variations as well. Specifically, we assume coplanar and noncoplanar triples with an inner BBH of the total mass $20 M_\odot$, whose outer and inner orbital periods are 80 days and 10 days, respectively. We perform a series of N-body simulations and compare the results with analytic approximate solutions based on quadrupole perturbation theory. For coplanar triples, the pericenter shift of the outer star can be used to detect the hidden inner BBH. For noncoplanar triples, the total RV semi-amplitude of the outer star is modulated periodically on the order of 100km/s due to its precession over roughly the Kozai-Lidov oscillation timescale. Such long-term modulations would be detectable within a decade, independent of the short-term RV variations on the order of of 100 m/s at roughly twice the orbital frequency of the inner binary.

7.1.2 Search for Alignment of Disk Orientations in Nearby Star-Forming Regions

Spatial correlations among proto-planetary disk orientations carry unique information on physics of multiple star formation processes. We select five nearby star-forming regions that comprise a number of proto-planetary disks with spatially-resolved images with ALMA and HST, and search for the mutual alignment of the disk axes. Specifically, we apply the Kuiper test to examine the statistical uniformity of the position angle (PA: the angle of the major axis of the projected disk ellipse measured counter-clockwise from the north) distribution. The disks located in the star-forming regions, except the Lupus clouds, do not show any signature of the alignment, supporting the random orientation.

Rotational axes of 16 disks with spectroscopic measurement of PA in the Lupus III cloud, a sub-region of the Lupus field, however, exhibit a weak and possible departure from the random distribution at a $2\sigma$ level, and the inclination angles of the 16 disks are not uniform as well. Furthermore, the mean direction of the disk PAs in the Lupus III cloud is parallel to the direction of its filament structure, and approximately perpendicular to the magnetic field direction. We also confirm the robustness of the estimated PAs in the Lupus clouds by comparing the different observations and estimators based on three different methods including sparse modeling. The absence of the significant alignment of the disk orientation is consistent with the turbulent origin of the disk angular momentum.
7.1.3 Obliquity of an Earth-like planet from frequency modulation of its direct imaged lightcurve

Direct-imaging techniques of exoplanets have made significant progress recently, and will eventually enable to monitor photometric and spectroscopic signals of earth-like habitable planets in the future. The presence of clouds, however, would remain as one of the most uncertain components in deciphering such direct-imaged signals of planets. We attempt to examine how the planetary obliquity produce different cloud patterns by performing a series of GCM (General Circulation Model) simulation runs using a set of parameters relevant for our Earth. Then we use the simulated photometric lightcurves to compute their frequency modulation due to the planetary spin-orbit coupling over an entire orbital period, and attempt to see to what extent one can estimate the obliquity of an Earth-twin. We find that it is possible to estimate the obliquity of an Earth-twin within the uncertainty of several degrees with a dedicated 4 m space telescope at 10 pc away from the system if the stellar flux is completely blocked.

7.1.4 Photo-evaporation and atmospheric properties of hot rocky exoplanets

The space telescope Kepler, by transit observations, detected a significant number of small-size exoplanets, which are twice as large or small in size than the Earth. Those are thought to include many rocky exoplanets. Because of the observational bias in favor of planets close to their central star, many of those rocky exoplanets have hot enough surfaces to be molten and are theoretically expected to have atmospheres composed of silicate, sodium, potassium and so on. Such exoplanets are sometimes called lava planets or magma planets and their atmospheres are called the mineral atmospheres.

The existence of hot rocky exoplanets is not trivial: Given intense X-ray and UV (XUV) irradiation from their central star, those planets may be subject to substantial mass loss via the escape (or photo-evaporation) of the mineral atmospheres. To investigate the stability of hot rocky exoplanet atmospheres, we have developed a computation code for simulating the hydrodynamic escape of the highly XUV-irradiated mineral atmosphere, including the detailed non-LTE radiative transfer and photochemistry [61]. Our simulations demonstrate that alkali and alkaline-earth elements such as sodium play a crucial role in efficient radiative cooling and thereby slow the atmospheric escape substantially. The heating efficiency of the mineral atmosphere of hot rocky super-Earths is estimated to be smaller by a few orders of magnitude than other types of atmospheres such as hydrogen-rich ones. We conclude that hot rocky super-Earths survive photo-evaporation for billion years.

Detection and characterization of such tenuous atmospheres are challenging, however, with often-used transmission spectroscopic observations during planetary transits. Instead, we have explored the possibility of detection via emission spectroscopic observations via secondary eclipses [62]. We have modeled the chemical structure and emission spectrum of the mineral atmospheres and found that such atmospheres are bright at 4 $\mu$m and 10 $\mu$m. Such emission features are prominent enough to be detected with the next-generation space telescope for infra-red spectroscopic observations of exoplanets, Ariel [63].

7.1.5 Formation of aqua-planets

An increasing number of low-mass exoplanets have been discovered around low-temperature dwarfs such as M dwarfs [64]. Some include planets with Earth-like insolation, which attract growing interest in how common Earth-like aqua planets are beyond the Solar system. While terrestrial planets are often assumed to capture icy or water-rich planetesimals, a primordial atmosphere of nebular origin itself can produce water through oxidation of the atmospheric hydrogen with oxidizing minerals from incoming planetesimals or the magma ocean. Thermodynamically, normal oxygen buffers produce water comparable in mole number equal to or more than hydrogen. Thus, the primordial atmosphere would likely be highly enriched with water vapor; however, the primordial atmospheres have been always assumed to have the solar abundances.

We integrate the 1D structure of such an enriched atmosphere of sub-Earths embedded in a protoplanetary disc around an M dwarf and investigate the effects of water enrichment on the atmospheric properties with focus on water amount [65]. We find that the well-mixed highly enriched atmosphere is more massive by a few orders of magnitude than the solar-abundance atmosphere, and that even a Mars-mass planet can obtain water comparable to the present Earth’s oceans. Although close-in Mars-mass planets likely lose the captured water via disc dispersal and photoevaporation, these results suggest that there are more sub-Earths with Earth-like water contents than previously predicted.
7.1.6 Mapping of Directly Imaged Planets

One of the key issues in astrobiology is how to characterize terrestrial planets in the future when direct imaging from space becomes possible. We have previously proposed Spin-Orbit Tomography, which can estimate the two-dimensional distribution of planetary surfaces by applying an inverse problem to luminosity variations. In this year’s project, we have succeeded in extending the application of machine learning technology to Spin-Orbit Tomography. In particular, we introduced three new methods (non-negative matrix factorization, sparse modeling, and Gaussian process) from the field of information science to the mapping method of planetary surfaces, and greatly extended the method (16, 17, 18).

7.1.7 Discovery of the runaway dipper

We developed a pipeline to process the full frame data of the first year of TESS, and analyzed 7 million objects. In particular, we searched for dippers that produce irregular dimming due to debris-like material orbiting stars by learning using neural nets. As a result, we found 38 new dippers, including a runaway dipper that seems to have escaped from a molecular cloud, which is in the field and has a velocity of over 70 km/s (19). In addition, we found a dipper candidate with a large line-of-sight velocity variation, which may be orbiting a binary star. This is currently under follow-up observation (Kasagi et al. in prep).

7.1.8 New capability for exoplanet characterization on Subaru

High-dispersion coronagraphic instrument, REACH science operation started We are developing an instrument at Subaru Telescope to realize HDC, which we proposed in 2014, combining coronagraph with high-dispersion spectroscopy. We have started the scientific operation of this instrument, REACH. In addition, we have detected couple of new molecules in hot jupiters (17, 18, 19).

7.1.9 First Detection of OH Emission from an Exoplanet Atmosphere: High-dispersion Characterization of WASP-33b Using Subaru/IRD

We have detected a new chemical signature in the atmosphere of an extrasolar planet using the IR Doppler instrument Subaru/IRD. The hydroxyl radical (OH) was found in the dayside of the exoplanet WASP-33b. The planet is a hot-Jupiter, a gas-giant planet orbiting its host star closer than Mercury orbits the Sun and therefore reaching atmospheric temperatures of more than 2000K. Although OH has been detected in the atmosphere of Solar System planets including Earth, Venus, and Mars, this is the first time it has been found in the atmosphere of a planet beyond the Solar System. Our results show not only that we can detect such a molecule in exoplanet atmospheres, but also that we can understand the detailed chemistry of this planetary population.

7.1.10 SCExAO/CHARIS Direct Imaging Discovery of a Close Low-Mass Companion to an Accelerating Sun-like Star

We present the direct imaging discovery of a substellar companion to the nearby Sun-like star, HD 33632 Aa, at a projected separation of ~20 au, obtained with SCExAO/CHARIS integral field spectroscopy, complemented by Keck/NIRC2 thermal infrared imaging. The companion, HD 33632 Ab, induces an astrometric acceleration on the star as detected with the Gaia and Hipparcos satellites. Its spectra are best matched by a field L/T transition object and an older, higher-gravity, and less dusty counterpart to HR 8799 cde. We have also measured a dynamical mass based on the astrometry, which turns out to be consistent with that estimated from photo-spectroscopy.
7.1.11 Discovery of exogenic materials on asteroid Ryugu and Bennu

JAXA’s Hayabusa2 and NASA’s OSIRIS-REx missions observed small rubble-pile asteroids Ryugu and Bennu with similar spectroscopic and morphological properties, respectively. These asteroids belong to C-type asteroids, which may have played an important role in delivering both water and organics to terrestrial planets, including Earth. Thus, the origin and evolution of Ryugu and Bennu have important implications for the origin of life.

Our recent joint data analysis between Hayabusa2 and OSIRIS-REx teams found that both asteroids have fragments of exogenic materials from other asteroids; Ryugu has S-type bright boulders, which are likely from one of the most common spectral type of asteroids in the inner main belt, and Bennu has V-type bright boulders, which are likely from one of the rarest spectral type of asteroids, such as Vesta (Tatsumi et al., 2021). This finding shows that these similar asteroids are from different parent bodies and experienced different collisional histories. Furthermore, detailed morphological and spectral analyses of Ryugu surface revealed that Ryugu is covered with thin (<1m) reddish surface layer on the top of blueish substrate. Because the top reddish layer is distributed over equatorial and mid-latitude regions, where solar radiation is strong, the reddening is likely due to either solar wind irradiation or solar heating.

Careful crater counting further shows that crater color distribution has a clear bimodal distribution, indicating that surface reddening event terminated rather abruptly. These observations suggest that Ryugu surface may have been reddened by intense solar irradiation during Ryugu’s orbital excursion toward the Sun and that the event terminated by a sudden orbital change due to close encounter with a large planet. Because of the success of the first artificial impact experiment on an asteroid, now we have a calibration data point for cratering age on Ryugu (Arakawa et al., 2020). Based on this calibration, we estimate the surface age of the termination of reddening event is between 0.3 - 8.1 Myrs, and Ryugu’s topography age is 8.5 Myrs older than the above age.

7.1.12 High-throughput laboratory evolution reveals evolutionary constraints in Escherichia coli

Understanding the constraints that shape the evolutionary dynamics is critical for predicting and controlling evolution. Despite its importance, however, a systematic investigation of evolutionary constraints is lacking. To understand the evolutionary constraint, we perform a high-throughput laboratory evolution of Escherichia coli under the addition of 95 antibacterial chemicals and quantified the transcriptome, resistance, and genomic profiles for the evolved strains. Utilizing machine learning techniques, we analyze the phenotype–genotype data and identified low dimensional phenotypic states among the evolved strains. Further analysis reveals the underlying biological processes responsible for these distinct states, leading to the identification of trade-off relationships associated with drug resistance. These findings bridge the genotypic, gene expression, and drug resistance gap, while contributing to a better understanding of evolutionary constraints. This understanding of the nature of evolutionary constraints will contribute to research exploring extraterrestrial living systems.

7.1.13 Dynamical systems approach to evolution–development congruence

It is acknowledged that embryonic development has a tendency to proceed from common toward specific. Ernst Haeckel raised the question of why that tendency prevailed through evolution, and the question remains unsolved. Here, we revisit Haeckel’s recapitulation theory, that is, the parallelism between evolution and development through numerical evolution and dynamical systems theory. By using intracellular gene expression dynamics with cell-to-cell interaction over spatially aligned cells to represent the developmental process, gene regulation networks (GRN) that govern these dynamics evolve under the selection pressure to achieve a prescribed spatial gene expression pattern. For most numerical evolutionary experiments, the evolutionary pattern changes over generations, as well as the developmental pattern changes governed by the evolved GRN exhibit remarkable similarity. Changes in both patterns consisted of several epochs where stripes are formed in a short time, whereas for other temporal regimes, the pattern hardly changes. In evolution, these quasi-stationary generations are needed to achieve relevant mutations, whereas, in development, they are due to some gene expressions that vary slowly and control the pattern change. These successive epochal changes in development and evolution are represented as common bifurcations in dynamical systems theory, regulating working network structure from feedforward subnetworks.
to those containing feedback loops. The congruence is the correspondence between successive acquisitions of subnetworks through evolution and changes in working subnetworks in development. Consistency of the theory with the segmentation gene-expression dynamics is discussed. Novel outlook on recapitulation and heterochrony are provided, testable experimentally by the transcriptome and network analysis [80].

7.1.14 Thermodynamic trade-off relations and information processing in biochemical system

Chemical reactions are responsible for information processing in living cells, and thermodynamic trade-off relations can explain their accuracy and speed. Based on differential geometric theory of information namely information geometry, we derived several thermodynamic trade-off relations such as thermodynamic speed limits and thermodynamic uncertainty relations in biological systems [88] and chemical systems [91]. We also clarify an information-geometric interpretation of the entropy production based on the projection theorem [89]. By applying the thermodynamic trade-off relation, we proposed a machine-learning method to estimate the entropy production from time series data [87]. We also numerically shows the behavior of information flow near critically in the Ising system [91]. These results would explain information processing and its thermodynamic cost in living systems universally, e.g., astrobiological living systems.

7.1.15 Mechanism of Contraction Rhythm Homeostasis of heart muscle

The heart rhythm is maintained by oscillatory changes in [Ca$^{2+}$]. However, it has been suggested that the rapid drop in blood pressure that occurs with a slow decrease in [Ca$^{2+}$] preceding early diastolic filling is related to the mechanism of rapid sarcomere lengthening associated with spontaneous tension oscillation at constant intermediate [Ca$^{2+}$]. Here, we analyzed a new type of oscillation called hyperthermal sarcomeric oscillation. Sarcomeres in rat neonatal cardiomyocytes that were warmed at 38-42 degree Celcius oscillated at both slow, Ca2+-dependent frequencies and fast, Ca-independent frequencies. Our high-precision experimental observations revealed that the fast sarcomeric oscillation had high and low peak-to-peak amplitude at low and high [Ca$^{2+}$], respectively; nevertheless, the oscillation period remained constant. Our numerical simulations suggest that this regular rhythm is maintained by the unchanged cooperative binding behavior of myosin molecules during slow oscillatory changes in [Ca$^{2+}$] [94].

7.1.16 Development of new imaging technology by combination of optics and AI technologies

We are developing imaging technologies to answer the very basic question “What is life”. These technologies are implemented with microscopes for the observation of cells and molecules in the laboratory, but the same technologies can be applied for telescopes as well.

Nearly half year from April, the laboratory works were forced to stop due to the lab closure by COVID-19 in FY2020. “Wet experiments” using protein or living cells were seriously delayed. We, therefore, rather focused on the development of the image processing algorithms using machine learning or deep learning technologies. For example, Kowashi applied deep learning based image processing algorithms for the processing of the images of interferometric scattering microscope. Two papers were published by former international intern students from Lomonosov Moscow State University through STEPS (Students and Researchers Exchange Program in Sciences with Russian Universities) program. Yakov has developed an image henhancement algorithm for super-resolution microscopy [91], and Alex has developed a cell segmentation and tracking algorithm [110]. We also tried to develop “explainable AI” for the cell image classification. Microscope images were first classified by deep learning AI. Then, we extracted the features that AI has used for the classification by using Grad-CAM analysis. As a proof of this concept, we have classified the microscopic cell images for the cell cycle, and the Grad-CAM analysis indicated that AI has classified the cell images by focusing on nucleus and Golgi. We cell biologists expected nucleus would be most informative for the cell cycle classification, but this analysis unexpectedly identified Golgi as another marker for the cell cycle. In fact, we confirmed that Golgi changes its shape and size according to the cell cycle. This would be a primitive but first example that cell biologists learned from AI [97].
7.2 Publication List

[21] Uyama, Taichi; Norris, Barnaby; Jovanovic, Nemanja and 7 more. 2020, “High-contrast H α imaging with Subaru/SCExAO + VAMPIRES”, JATIS, 6, 045004.


7.2. PUBLICATION LIST


7.2. PUBLICATION LIST


7.3. INTERNATIONAL CONFERENCE TALKS


7.3 International Conference Talks

7.3.1 Contributed talks


[107] Oya, Y., “Temperature Structure of the Pipe Nebula Studied by the Intensity Anomaly of the OH 18 cm”, The Early Phase of Star Formation 2020, July 12–17, 2020, Germany (CANCELED)

7.3. INTERNATIONAL CONFERENCE TALKS


7.3.2 Invited talks


[137] Suto, Y., “Unveiling spin-orbit architectures of exoplanetary systems”, Astronomy Colloquium, Shanghai Jiao Tong University (September 28, 2020)
[138] Suto, Y., “Unveiling the presence of an inner binary black-hole from the tertiary orbiting star”, The 9th KIAS workshop on Cosmology and Structure Formation, Korean Institute of Advanced Study (November 2, 2020)

III

Reports
on the research activities
of RESCEU groups in 2020
(in Japanese)

2020年度
RESCEU研究グループ別
研究活動報告
8 横山順一研究室

8.1 研究活動報告

当研究室は、一般相対性理論、場の量子論、素粒子物理学等の基礎物理学理論に基づいて宇宙論と重力理論の理論的研究を幅広く行うとともに、理学部物理学科の教育に貢献している。また、大気低温重力波検出器 KAGRA の稼働を迎え、新規研究室とともに重力波データ解析の研究に人材育成にも携わっています。今年度は科学研究費補助金基盤研究（S）「重力波宇宙物理学の包括的研究」の採択により、5370万円の計算機クラスターの導入が計画され、KAGRA のデータ解析の準備を進めています。

今年度は新型コロナウイルスの蔓延のため、M0 ゴミの一部期間を除き、研究室の全てのセミナーはオンラインでの開催を余儀なくされました。また、毎日 2 時から 1 時間アーカイブチャックの時間を設け、構成員の一員間の情報交換と安心確認を行っています。

8.1.1 初期宇宙論

初期宇宙理論

初期宇宙理論の観測される現在の銀河や銀河団の磁場の起源やプレーザーの観測による示唆される銀河間ホウド磁場を説明する上で、興味深い研究対象である。我々は初期宇宙磁場の存在を仮定し、標準模型のカイラル量子異常を通じて初期宇宙磁場の磁気ヘリシティは局所的な物質反中性非対称を生じるため、電場磁場移期におけるバロイン等価率挙きの生成が一般に避けられない。ところが、ビッグバン元素合成の理論と重元素の観測値との整合性から、バロイン等の数以上の生成が、この起源を初期磁場は制限を受ける。とくに初期磁場に対する制限を明らかにする、観測的説明されているホイス空間での銀河間磁場強度の起源としては、電弱対称性は微小な領域の磁場生成あるいは星周病態が可能なことを示した [11, 12, 13, 14, 15, 16, 17, 18, 19, 20, 21, 22]。

また、磁場生成機構として、アクチュエーターのマイクで呼ばれる複素スカーラー場がその field space において運動方程式を獲得する機構においてその位相とゲージ場が Chern-Simons 結合を持つ可能性に指摘し、この機構における磁場生成を調べた [23]。その結果、作られたヘリシティの磁場が電弱相転移時に現在の宇宙を説明するのに十分なバロイン非対称を生成し得ることが示された。

さらに、磁場と重力波が重力的な結合をすることに注目し、長距離相連の初期磁場がなければ、磁場によって初期宇宙において電子が重力波に変換される現象が起こることを指摘し、こうしてできた重力波がGHz scale の背景重力波として現在の宇宙に対応していることを示した [24]。

ブラックホール周りの真相相転移現象についての研究

極小のブラックホールの周辺では真空相転移が強く誘発されることが示唆されている。しかし、高温のホーキング放射のもたらす真空安定化の効果を考慮していないため、この効果を取り入れて相転移確率を計算し直した [25, 26, 27]。この結果、極小のブラックホールは依然として真空相転移を強く誘発することが判明した。

重力的レプトン数生成を実現する最小数模の動揺について

揮スカラーインフラトロンと、Riemann 時空で与えられる Chern-Pontryagin 密度の結び目を有する数模では、インフレーション中に非ゼロの Chern-Pontryagin 密度をもつ、重力的カイラルアノメラを経る相転移数同時に生成される。このような数模を重力的レプトン数生成といい、上記数模はこの機構を発見する最小数模である。しかしながら、生成されるレプトン数が量的変化に由来する外力変化を有し、先行研究の評価は無条件切りのスケールをどう取るかに強く依存することが懸念されていた。そこで本研究では解析的計算により外力変化依存性を leading order 以下で明らかにし、その変化を取り除く相殺果を同定した。すると、特定の線込み条件の元で現在のレプトン数が極めて小さくなり、スパッテン過程を経ても観測される宇宙のレプトン数は現在停留していないことがわかり、本機構の実現性に疑問を投げかける結果となった [28, 29, 30, 31, 32]。

原始ブラックホール改良質量関数の不確定性

原始ブラックホールの質量スペクトラル関数は、多くの不確定性を抱えているのが現状である。我々はこれを克服するために第 1 歩として、各々の原始ブラックホールの質量スケールを正確に評価する条件を取り入れた改良ブラックホール理論において、その高次極限における解釈的な表示を導出するとともに、密度ゆらぎを粗視化する方法に起因する不確定性を調べた。特に振がスケール不変性のパワースペクトルを持つ場合、原始ブラックホール形成に重要となるスケール周辺では改良の効果がほとんど効かないことを示した [33, 34, 35, 36, 37]。
ヒッグス-\( R^2 \)混合模型における再加熱過程

ヒッグス-\( R^2 \)混合模型は現在の宇宙背景放射の観測から最も支持されるインフレーション模型の一つである。この模型は仮数場インフレーション模型であり、特にその再加熱過程は単一インフレーション模型とはまったく違った相を示し、興味深い現象である [13]。特に、模型パラメータの値によっては、インフレーション直後に激しいタキオンクラスター・プリンシピミュングと呼ばれる現象が起こり、宇宙が瞬間的に熱化する。我々はこの現象を解析的および数値的手段によって解析し、この現象が起こり、宇宙を充分に熱化するパラメータの値とその微調整の程度を定量的に定めた [11, 12, 13, 14]。

M-理論における\( \alpha \)-attractorの実現に向けて

量子重力を含む理論的候補であるM-理論の枠組みで観察と整合する初期宇宙のインフレーションを実現することは重要な課題である。M-理論はその理屈的構成を含めてまだ完全な理解には至っていないが、その粒子極限は1次元超重力理論で記述されることが知られている。余剰時間に超対称性を保つようなバランスが導入し、\( 4 \times 4 \)量子コンフュート化を考えると安定した真空を持つ2次元超対称理論が得られる。我々はこれに有効理論に残るモノイド場が、現在の観測結果と整合する\( \alpha \)-attractorインフレーション模型の元となる結合を持つことを示し、特に原始重力波を特徴づけるパラメータ\( \alpha \)がフラックスポテンシャルをどのように選ぶことで変化するかを議論し、7つの離散的な値が得られることを示した [12, 11]。

21cm線の円偏光

中性水素の超微細構造に起因する21cm線は、光子の脱結合の時期から星ができるまでの暗黒時代を調べるための最も重要な観測量の一つとして期待されている。一方で、宇宙背景放射の四極モーメントをもつ揺らぎは、中性水素のスピンを移動する働きをし、結果として21cm線の円偏光が生成される。宇宙背景放射の四極モーメントは原始重力波によって生成されること、21cm線の円偏光は宇宙の情報に含めていると言える。先行研究では、生成される円偏光の大きさは観測されていなかったものの、その角度パワースペクトルはままだとされていなかった。我々は、先行研究で用いていた球面積に基づいた計算手法は異なる、直交座標に基づいた計算手法を用い、21cm線の円偏光の角度パワースペクトルを求めることに成功した [14]。

真空崩壊に伴う粒子生成の解析

真空崩壊は背景がトンネル効果によって一次相転移を起こし現象であるが、この際にその場と結合している粒子の有効質量は急激に変化することになり、有効質量を変化した粒子はそれに伴って基底状態が変化するため、生成生成波子数の定義が変わるこ、粒子生成が起こる。我々はこの粒子生成について、近を解明されているトンネル効果の実時間形式の下でモデル化し、数学的手法としてストークス現象を踏まえて解析的評価を行った。これにより相転移に伴う粒子生成の解析が可能で、同時に、トンネル効果の実時間形式のものについてトンネル確率とは違った側面からその正当性を示すことができる [13, 14]。

二次スカラーレゾン―の解析的表式

宇宙論においてスカラー発生は、初期宇宙の理論と現在の観測を結ぶ重要な働きをする。宇宙背景放射の観測から、大スケールのスカラー発生量が大きくなることがわかったが、小さなスケールのスカラーレゾンに大きさが大きい可能性はまだ残っている。大きなスカラー発生が存在する場合、その非線形効果が重要になるため、その発展を解析的に追い求めることの基礎を築くことには意義がある。このような背景から、我々は一次のスカラー発生が非線形効果を通じて生じ出す二次のスカラー発生の解析的表式を求めた。さらに、その表式を用いて、二次スカラー発生がどのような時間発展をするのか、及びどのようなような発生のスペクトルが予測されるのかを明らかにした [13, 14]。

真空相転移のローレンツ経路積分による考察

真空相転移は時空をユークリッド化し、その上でのパウリ方程式を用いて解析される。ところが重力が存在するときはこの描像は不明確になるので、ユークリッド時空ではなくローレンツ時空で直接解析することを目指した。ローレンツ時空の真空相転移を考え、重力への反作用を無視するような状況を考えると、従来のパウリ方程式による解析の結果を再現することができた [21]。

右巻きニュートリノの重力的粒子生成による包括的宇宙論

クインテッセンシャル・インフレーションに3世代の右巻きニュートリノを導入することで、暗黒物質の存在量、バリオン数生成、再加熱過程、暗黒エネルギーといった宇宙論の諸問題を、インフレーション恵の右巻きニュートリノの重力的粒子生成によって包括的に説明するモデルを構築した。このモデルにおいては、3世代の右巻きニュートリノの軽い方から順に\( N_1, N_2, N_3 \)とおくと、\( N_1 \)はステライル・ニュートリノと同様に暗黒物質として振る舞い、\( N_2 \)は\( N_1 \)との干渉による正味のバリオン数を生成し、\( N_3 \)は標準模型の粒子に崩壊することで再加熱過程を実現する。重力的粒子生成は共形対称性からのズレに起因する機構である為、これら\( N_1, N_2, N_3 \)の生成
シュウィンガー効果を用いた再加熱過程の検証

アクションのようないろなスケーラーによって駆動されるインフレーション模型において、スケーラーがインフレーション終了後にポテンシャルの極小点に落ちずに転がり続ける場合の再加熱過程を考えた。この場合、インフラトンがポテンシャル極小点周りでコヒーレントに振動して崩壊するという通常の再加熱過程の議論を適用することは出来ない。しかしながら、スケーラーが運動し続ける際にはヘリカルな電磁場が生成することが知られており、生成した電磁場から更にシュウィンガー効果によって荷電粒子を生成して熱源を実現することが可能である。一方、状況によっては残存した電気磁場が観測と矛盾した結果をもたらしてしまうことがある。我々はこうした模型について検討した結果、スケーラーの運動が速過ぎなければ再加熱過程が上手くいくパラメータ領域が存在することを示した [37]。

8.1.2 重力波検出器KAGRAのデータ解析

補助モニターを用いたオフライン解析による雑音除去手法の開発

2020年4月に初の本格稼働を実施したKAGRAであるが、現在は2022年6月以降開始予定のLIGO-VirgoとのO4共同観測に向けた改修作業中である。重力波検出を遂行するためにはさらなる感度向上を実現しなければならず、様々な雑音源に直面校正を講じるとともに、オフラインデータ解析によりデータから雑音を統計的に除去する手法の開発が必要である。本研究では、非ガウス分布に従う信号が混合した際に分離・復元する処理手法である独立成分解析（ICA）に着目し、補助モニターを用いた雑音除去手法の開発に取り組んだ。これにより、初期稼働時のiKAGRAデータに最も単純なモデルのICAを適用し、地震計を用いることで地震動雑音を部分的に削減できるという結果が得られている [31]。本年度はさらに、新たにKAGRAデータと補助モニターに対する拡張したICAモデルを適用することで、重力波の観測周波数帯域において特に影響が顕著であった音響雑音の除去に成功した [28, 41, 45, 51]。

8.2 業績リスト

<受賞>
[1] 横山順一, 令和2年度 科学技術分野の文部科学大臣 表彰 科学技術賞「最も一般的なインフレーション宇宙論の研究」

<報文>
(原著論文)

<指名>


8.2. 業績リスト


(会議抄録)


(国内雑誌)

[18] 横山順一「横山教授に聞く科学のふしぎ」 子ども新聞「風っ子」連載, 第 37 回 - 第 59 回, 上毛新聞社

(学位論文)


(編著書)


＜学術講演＞

(国際会議)

一般講演


[34] F. Uchida, “Constraints on baryogenesis from primordial magnetic fields”, The Online Workshop on General Relativity and Gravitation in Japan (Online JGRG), Online, 2020/11/24.

招待講演

(国内講演)
一般講演


47. 羽柴聡一朗、"右巻きニュートリノの重力的粒子生成によるパリオン数と暗黒物質の生成", 基研会 素粒子物理学の進展 2020, ポスター, Online, 2020/08/31-09/04.


49. 内田頌夫、鍾田耕平、横山順一、"磁場によるパリオン数生成シナリオに対する、パリオン揺らぎから制限", 日本物理学会 2020 年秋季大会, Online, 2020/9/15.

50. 羽柴聡一朗、山田悠介、横山順一、"真空崩壊に伴う粒子生成とその帰結", 日本物理学会 2020 年秋季大会, Online, 2020/9/15.

51. 細潤哉、鍾田耕平、山田悠介、"重力的レプトン数生成における量子補正の正則化とその帰結", 日本物理学会 2020 年秋季大会, Online, 2020/9/15.

52. 渡慶次孝気、猪島敬介、横山順一、"原始ブラックホールの新しい質量関数と密度揺らぎの相対性に伴うフィルター関数依存性", 日本物理学会 2020 年秋季大会, Online, 2020/9/15.


(アウトリーチ)

[72] 橫山順一, 第 93 回五月祭講演, 「輪廻する宇宙」 オンライン 2020/9/20-21

[73] 橫山順一, 立川国際高校講演会, 「コロナ時代に考える宇宙のこと世界のこと」 立川国際高校 2020/12/18
9 Kipp Cannon研究室

私たちの研究グループは、ブラックホール、中性子星、エキゾ星なった天体、そして宇宙そのものを重力波観測、時には電波観測も含めて研究していま
す。重力波は、質量やエネルギーの動きによって生成される時空曲率の波です。重力波が宇宙を探索する
の適している理由は沢山あります。重力波は電磁波
（電荷の動きによって生成される）を生成する過程
とは異なる物理的なプロセスによって生成されるため、電磁波とは異なる波源に関する情報を我々にもらえ
ます。また、重力波は物質と非常に強く相互作用する
ため、電波や光に対して不透明な物質であっても
透過します。例えば、超新星の中心部分やビッグ
バンの最も初期の瞬間ではさえも重力波であれば、観
測することができると期待されています。地球も重
力波に対しては透明であるため、重力波望遠鏡は昼
夜間わわず、常に全天を視線的に観測することができます。重力波は、ブラックホール凝縮の衝突のよ
な、宇宙で最も激しいイベントで放射される唯一
の重要なエネルギーの形です。しかし、重力波に対
してはほぼ全てのものが透明であるため、それを
検出できる装置を構築することは非常に困難であり、
重力波の検出は2015年に初めて達成されました。

私たちの研究グループのメンバーはLIGOとKA-
GRAコラボレーションのメンバーであり、世界中の
重力波検出器、LIGO（アメリカ）、Virgo（イタリア）、
GEOf000（ドイツ）、KAGRA（日本）によって新設さ
れたデータを分析してします。LIGOとVirgoは、
2019年3月にわたる第3次観測「O3」を開始し、デー
タ取得は1年間ほど継続される予定でした。しかし、
コロナウイルスの流行により2020年3月に観
測が中止されてしまったため、残念ながら今年度は
LIGO/Virgoの新しいデータは得られませんでした。
その代わり、2週間ほどの短い期間ですが、KAGRA
の新しいデータが得られました。私たちのグループ
のメンバーは、そのデータの分析を通じて重力波を
用いた天文学や宇宙論のほぼ全ての分野で活動して
います。

9.1 研究活動報告

9.1.1 重力波データ解析

重力波信号の統計特性に基づく重力波探索の効率化

重力波信号のみが持つ特性を利用した、信号を検
出するに必要な計算時間を大幅に短縮するた
めの手法を開発している。具体的には連合重力
波形テンプレートを用いた連続フィルターによる
信号検出比と、信号検出比の時系列とテンプレート
の自己相関との差異の2つの変数が従う確率密度分
布をあらかじめ重力波信号と雑音の双方に対して計
算しておく、重力波信号が可能な信号が非常に低
い疑似信号を検出システムの初期段階で捨ててしま
うことができれば、従来の短い時間で重力波を
探索できるようになる。重力波が検出されたコンパ
クトマシンがそういったことによって作られた
のかを知るためには様々な宇宙物理学の理論モデル
と実際の観測結果とを組み合わせる必要があるが、
この手法が実用化すると、今後は計算に時間がかか
りすぎるために現実的には困難であった数多くの理論
モデルの検証が一気に行えるようになり、宇宙物理
学上のいくつかの長年にわたり難問が解決することが
期待される。

重力波探索におけるモデル選択バイアスのモデリング

コンパクトマシンを含む生じる重力波の振幅は
非常に小さく、ごく限られた数しか観測すること
ができない。これにより、観測波の検出率と発生
率には違いが存在することを意味している。その違
いは観測機器によるハードウェアとデータ解析によ
るソフトウェアの両面から生じ、その違いの評価は
重力波探索全体を踏まえた検討で行うことによっ
て行われる。従来の観測方法では意図した仮想の重力
波信号を検出することによって行われていたが、この
手法は高コストであることだけに加え、検出器の感度向
上に伴い、データに多数の重力波信号が混入し、将
来の精度が低下することが懸念されている。我々
はその問題に対して、仮想の重力波信号を検出する
際のソフトウェアの振る舞いをモデル化することで
解決を試みている。半解析的な手法推定によりコスト
は大きく削減され、観測データを直接的に扱うこ
とも回避している。この手法を実際的に改良し、現
在では通常の解析の中で用いられるようになった。

GstLAL パイプラインによる背景雑音推定の改善

GstLAL パイプラインによる重力波データ解析で
は尤度比順位統計を用いているが、その雑音モデル
の推定には重力波検出器の観測データを必要とする。
しかし、重力波信号が含まれたデータは雑音モデル
推定に用いるべきではなく、重力波信号の無い観測
データを用意することも現実的には不可能であるため、
重力波信号の影響をなるべく受けないような雑音も
重力波源の高速位置特定手法の開発

電磁波及び重力波による共同観測は重要であるが、その成功率を上げる方法として、重力波源の位置を高速で特定するという方法もある [14]。特に、シャートガンマ線パーストなどの短時間イベントを調べると、情報の経過によって失われていく系の情報が重要であるため、高速位置特定の必要性は非常に高い。研究者は、事前に推定する高速化のために、いくつかの近似を試行している。その結果、これらの近似を1つずつ取り除いていく、推定精度の向上を図っている。

将来重力波検知器における重力波信号の重なりとパラメータ推定への影響

Einstein Telescope や Cosmic Explorer などの将来の地上重力波検知器は、中性子星やブラックホールの連星合体による重力波イベントを多数（1年間に数10 イベント）観測することが期待されている。しかし、イベント数が多すぎる場合、検知器データ中の重力波信号同士のしばしば重なり合ってしまう、重力波源のパラメータ推定に影響を与える可能性がある。場合によっては、重力波信号の分離が困難になり、検出が困難になることもあり得る。そこで、我々は、重力イベントをランダムに生成するシミュレーションを行い、重力波信号の重なりがどの程度発生するのかを評価した。そして、重力波信号重なりが集まる場合に、パラメータ推定の誤差やパラメータの不確定性の程度を評価するための親近を評価した。その結果、重なり合う重力波信号の母数が非常に似ていない限り、パラメータ推定はほとんど影響を受けないことが分かった。つまり、将来の将来地上重力波検知器において重力波信号の重なりはパラメータ推定に対しほぼ問題にならないことを示した。

9.1.2 重力波天文学

ブラックホール誕生時の突発的天体現象

Advanced LIGO などの重力波検知器を用いた観測によって発見された連星ブラックホールがどのように形成されるかは、天体物理学の大きな謎の一つになっている。その謎を解明するために、ブラックホール誕生の瞬間を観測することが可能となり、ブラックホール形成時に付随する突発的な天体現象に関する理論的研究を行っている。ブラックホールが質量大星から誕生する際、中心核のニュートニンラウットによって重力が減少するた め星の外層の一部が放出される。この質量放出に伴う100 日程度の電磁波放出を計算し、観測可の赤外面向で観測される突発天体 intermediate luminosity red transients の観測を推定できることを示した [10]。また近年中性子星合体 GW170817 の再解析により、合体後の放射状ブラックホールからの新たな重力波信号の検出が報告されている。この信号についての一つの解釈として、量子重力理論が予測する重力波や光を発生する現象に着目し、GW170817 の再解析結果を推定できることを示した。さらに将来近傍銀河の大質量星からブラックホールが形成された場合、このような重力波放出が次世代の重力波干涉計で観測可能であることを示した [11, 12]。

電波望遠鏡 CHIME によるショートガンマ線パーストからの残光観測への期待

我々は、ショートガンマ線パーストからの「残光」を電波望遠鏡 CHIME で観測することを目指している。ショートガンマ線パーストとは、二秒以内という短時間に高エネルギーを放出する爆発のことを指す。電波望遠鏡 CHIME は、ショートガンマ線パーストのエネルギー源である相対性理論と同一方向に放射されるため、観測結果は重力波源の観測が困難であることがある。一方、残光はより効率的に放射されるため、指向性による影響を受けにくく、電波観測によって正確なエネルギーキークール計算することも可能である。しかし、電波波長は非常に幅、望遠鏡に起因する無細や分解しきれない天体による背景無細や無視された、十分なS/N 比で検出することが困難である。そこで、本研究では、重力波観測で用いる「尤度比解釈」を用いて、ショートガンマ線パーストからの残光を検索することを考える。本研究によってより多くの電波残光が検出されれば、相対性理論が、近傍のガンマ線パーストの起源に制限を課すことになると期待する。

近未来重力波望遠鏡による異常運動している連星合体の事前予報

2015年に重力波が観測されつつある 2020年まで、多くの連星合体由来の重力波イベントが定期的に検出され、2017年には電波波望遠鏡との共同観測に成功した。電波波と重力波はそれぞれの時差で引き起こされていて、観測が異なるため、共同観測によってショートガンマ線パーストのモデル制限や、「過程要素合成の起源確認」などの、より広い物理を展開することができる。しかし、共同観測の成功は2017年の
9.2. 業績リスト

9.2.1 業績リスト

9.2.1.3 重力波による基礎物理の探究

重力波偏極モードによる重力理論の検証

一般相対性理論を拡張した重力理論はこれまで多数提案されており、一般相対性理論の正しさを様々な側面からより高精度で検証することは我々の重力に対する理解を深める上で重要である。重力波の発検出により、重力波を放出する天体の近傍、つまり、動的かつ非常に強い重力波における重力の性質を調べることが可能になった。そのような状況での重力の検証方法の1つとして、重力波の偏極モードがある。偏極モードの数は重力理論に特有であり、一般相対性理論では2つのモードが存在するが、拡張重力理論では3つ以上の偏極モードが存在できる。つまり、偏極モードの数を観測データから調べることで正しい重力理論を絞り込むことができる。我々は重力波検出器の実際の観測データを解析し、得られた重力波信号が一般相対性理論の予言する偏極モードの性質と一致しているかどうかの検証を行った。その結果、一般相対性理論と矛盾するような兆候は無く、一般相対性理論の正しさを支持する結果を得た[20]。また、重力理論検証のために、具体的な修正重力理論における宇宙論モデルや重力波に関する観測的予言の研究も行っている[21]。

ブラックホール周りの極軽量ベクトル場から放射される背景重力波の探査

近年、ブラックホール周りの有質量ボソン場が不安定性から重力波を放出する現象が提唱されている。その中でもベクトル場に着目し、そこから放出される重力波の重ね合わせである「背景重力波」を捜査した。この重力波の周波数帯は主にベクトル場の質量によって決まるため、捜査を通じてボソン場の質量に対する観測的制限を得ることが可能な目的である。ブラックホールを含む各星から放出される重力波の周波数について、ベクトル場ではブラックホールの質量に関する高次項まで含めて計算しなければならないことがさており、数値計算の結果をフィッティングすることで高精度の重力波スペクトルを導いた。この理論スペクトルに基づき、LIGOの観測データを用いてベイズ解析を行った。統計的に有意な検出結果は得られず、その事実からベクトル場の質量 $0.8 \times 10^{-13} \text{eV} \leq m_\gamma \leq 6.0 \times 10^{-13} \text{eV}$ に制限をかけた[27]。

重力波チェレンコフ放射の探査

仮に質点が超光速で動いたときに衝突波のように発生する重力波が存在するか、探査する。具体的には、チェレンコフ放射を衝突波に共通する、波形・スペクトルの特徴を持つ重力波を探すことを指す。

9.2.4 業績リストの関連研究

開放宇宙探査の進展が観測可能となるためには、宇宙の円滑な進行を図ることが重要である。

ラグ・ハムブリントン（R. Hamburg）, ラグ・アブト（R. Abbott）

10月10日10時～12時

LIGO, Virgo, KAGRA, GEO600などが公開される。


[27] L. Tsukada, R. Brito, W. East, and N. Siemonsen, “Modeling and searching for a stochastic

(学位論文)


[29] C. Chan, “Improving Background Estimation Technique In GstLAL Inspiral Pipeline” (修士論文).


＜学術講演＞

(国際会議)

一般論演


招待講演


(国内会議)

一般講演

[38] 鹿島みのり, “電波望遠鏡 CHIME による SGRB からの残光観測に向けた解析パイプライン開発”, 第 50 回天文・天体物理若手夏の学校，オンライン開催，2020/8/24-27.


(セミナー)


10 茂山俊和研究室

10.1 研究活動報告

私たちの研究室では、特殊に明るくなる天体現象の理論モデルを構築することで、その天体の宇宙史における役割を理解する研究を行っています。具体的には超新星発生や様々な星の合体現象を研究対象にしています。以下では、2020年度に論文などで成果を発表を行なった研究について説明します。

10.1.1 大質量星からの発光的な質量放出

重力崩壊型超新星を起こす大質量星の中心には、その数年前に発光的に増光し、外層を大量に放出することがあると考えられています。私たちの研究は、その現象論的なモデルを構築し、超新星爆発前回顾加観測された增光現象と比較することにより、どの程度の質量が放出されたのかを推測するとともに、放出された物質の密度構造や星の構造の変化を調べた。この現象の物理的成因は問わず、水素外線の底に一定の熱エネルギーを注入し変化を幅射流体コードを用いて数値計算した。その結果、放出された物質の一部は再び星の重力によって引き戻され、一部が半径0.15倍に比例する構造を持つことを示した。複数回質量放出現象ができると仮定した時にどのように明るさの変化が見られるかも調べた。これらの結果はすでに4編の論文として発表した。

10.1.2 星周間物质と爆発物質の衝突で光る天体

ブラックホール形成時の増光現象

大質量星の中心核が重力崩壊を起こすと、ニュートリノによって大量のエネルギーが星の外に持ち出される。その結果、重力が弱くなり外層の静電圧差が崩れ、その一部が放出される。それがそれ以前に放出された星間物質と衝突する時にどのように光るかを数値計算によって調べた。その結果、AT 2017beという突発天体を含む中等間星度線状星体（ILRTs）の特徴を備えていることがわかった。この結果はThe Astrophysical Journal Lettersに発表した。

11.2 Ne+1星超新星度曲線モデル

星周間物質と爆発物質の衝突で光る IINe型超新星の度曲線モデルを構築した。二つ以上の衝突が存在する領域をそれぞれの衝突波の静止系での定常解として記述した。この領域では局所熱平衡を仮定している。衝突波表面での放射強度を境界条件として、星周物質での幅射輸送のガスと幅射の2温度近似を用いて時間発展を観察した。この計算手法をThe Publication Astronomical Society of Japanに出版した。今後は、突発的に放出されて形成された星間物質と衝突した超新星の光度曲線を系統的に計算して、超新星とともに大質量星の最後の年数の進化に焦点を当てて研究を進める予定である。大質量星からの発光的な質量放出から超新星爆発に至る一連の現象を数値計算する計算コードを公開する取り組みを行なっている。

11.3 Ne+1型超新星多波長スペクトル進化モデル

星周間物質と爆発物質の衝突で光る IINe型超新星では、衝突時に形成される衝突波ではガスがエッジ線を放光するほど非常に高温になる。その後、衝突波下流で電子が放光する部分が冷却され、主に紫外線・可視光領域で光る。高溫の電子は逆 Compton 散乱で幅射とエネルギーのやり取りをする。この過程を取り入れた赤外線からX線までの熱的放射のスパクルメを計算するコードを開発し、The Astrophysical Journalに発表した。今後の多波長同時観測によって得られる観測結果からより多く的情報を引き出すために使用する予定である。

11.3.1 中性子星に降着する物質からの炭素爆発

Ia型に分類される超新星の中心には非常に明るく光るものも見られる。放射性元素56Niの質量がChandrasekhar limit 1.4 $M_{\odot}$を超えるものもあり、爆発物質の質量は2 $M_{\odot}$くらいと推定もChandrasekhar limitを超えている。爆発した星として回転している白色矮星を考える場合が多いが、観測の特徴を再現するのは難しい。我々は、これらの超新星を星形成している銀河で起きていることに着目、大質量星を起源とするシナリオを考えた。中性子星との直接連星系をなす大質量星は進化するとその外層をほとんど失いCO中心核のみが残る。重力波を放射しつつ軌道がさらに縮み、ついでに中性子が飲み込まれ、中性子星にCOが降着する。このときにC+Cの核融合反応に点火して爆発波が発生して星全体を吹き飛ばす可能性を調べることにした。
10.2 業績リスト

＜報文＞

(原著論文)


(会議抄録)


(その他国際雑誌)


(学位論文)

修士論文

10.2. 業績リスト

＜学術講演＞

(国内会議)

日本天文学会 2021 年春季年会、東京工業大学、2021/3/16-19

[12] 津名大地、樫山和己、茂山俊和” 星周物質との衝突で光る超新星のスペクトルエネルギー分布”，2021 年 3 月 19 日、N27a


[14] 酒向重行, 大澤亮, 諸隈智貴, 新納悠, 濵田伶, 土居守,茂山俊和他, "木曾 Tomo-e Gozen の広域動画像サーベイのデータ公開に向けた開発”, 2021 年 3 月 16 日、V208a

日本天文学会 2020 年秋季年会、弘前大学、2020/9/08-10

[15] 酒向重行, 大澤亮, 諸隈智貴, 新納悠, 土居守,茂山俊和他,”木曾広観望 CMOS カメラ Tomo-e Gozen サーベイによる広域動画像サーベイ”，2020 年 9 月 10 日、V204a

[16] 藤澤幸太郎, ”中性子星表面の定常的な磁気山の構造”, 2020 年 9 月 9 日、W20a

[17] 津名大地, 石井彩子, 樹山直人, 樫山和己, 茂山俊和,”濃い星周物質内でのブラックホール形成と突発天体”, 2020 年 9 月 10 日, W37a

一般講演

[18] 藤澤幸太郎,”Magnetically confined mountain on the neutron star surface”, ポスター, 重力波物理学・天文学: 創世記第 4 回国際シンポジウム, Online, 2021/02/22

(セミナー)

[19] 藤澤幸太郎,”Structures of magnetically confined mountains on neutron stars”, gw-genesis zoom seminar talk, Online, 2020/10/20
11 仏坂健太研究室

当研究室は、白色矮星、中性子星、ブラックホールなどのコンパクト天体に関する宇宙物理学を理論的に研究しています。特にコンパクト天体からの重力波やそれらに付随する電磁波放射に関する研究を観測グループと連携して行っています。

11.1 研究活動報告

11.1.1 連星中性子星の電磁波対応天体

キロノパの研究

キロノパは連星中性子星合体に付随する電磁波放射対応天体の一つであり、合体時に放出される中性子線の放射光によって観察される。この現象は特に重元素の起源に関連するという重要性がある。我々はキロノパに関する観測・理論の両面から研究を行っている。

2019年4月から11ヶ月間行われたLIGO-VirgoObservational Run 3 (O3)では、中性子星を含む連星合体からの重力波イベント候補が14天体報告された。このうちO3の後半で報告されたブラックホール・中性子星合体候補S191205ahとS200105ae、中性子星合体候補S191213gとS200115jに対応されてきた可視光観測の結果についての解析を行い、キロノパが見つかっていないという事実からエッジクタ質量などに対する制限を与えている。その結果、上記の全てのイベントにおいて追跡観測は対応天体を発見できるほど十分な感度が確保できていないことがわかった。

電磁波対応天体の研究

中性子星合体は非相対論的なキロノパエッジクタだけでなく、相対論的なジェットも観測する。このジェットと星間物質の間に形成された衝突波によって加速された非熱的な電子によって放射されるシンクロトロン光が電波からX線まで幅広い波長で観測される。我々はこのシンクロトロン放射に関する研究を行っている。

中性子星合体GW170817では合体時に生成された相対論のジェットからのシンクロトロン放射が合体後9日以降、少なくとも2021年3月まで電波からX線までで検出されている。我々はヨーロッパの限波電波望遠鏡LOFARを用いて150MHzでの追跡観測を行った。その結果、LOFARの感度が十分でなかったが、これはGW170817の位置の問題もあり、理想的な位置で連星合体の電磁波対応天体が発見された場合、LOFARによって150MHzでの残光を検出できる見込みがあることを示した。

GW170817の電波放射は十分なもく距離の比較的近いため、電波源の固有運動がVLBIによって測定されている。この固有運動は超光速運動を示し、ジェットのローレンツ因およびジェットに対する見込む角度がこの観測から測定された。このような観測は中性子星合体に付随するジェットの性質を調べるのに極めて有効であるのみならず、重力波から測定された重力波振幅と見込む角を組み合わせることによって天体までの光度距離を精度良く測定することが可能になる。これによって重力波と電波波を用いたハッブル定数の測定に繋がる。したがって、今後の重力波イベントにおいて、超光速運動が測定されるかも知れないと、ジェットの物理および重力波宇宙論という二つの観点から重要となる。我々はVLBIによるジェットの固有運動の測定、さらに星間空間の密度変化に起因する電波の減衰を観測したジェットのサイズの測定が今後のイベントでの程度実現可能性を調べた。その結果、VLBIによる測定は100Mpc程度まで、シンチレーションにより測定は数100Mpcまで可能であることを示した。これらの結果から将来の重力波・電波観測にジェットの性質とハッブル定数の測定に対して重要な手法を与えることが期待できることがわかった。

11.1.2 連星ブラックホール合体の研究

LIGO/Virgoはこれまで50天体ほどの連星ブロックホールからの重力波の検出に成功している。しかし、これら連星ブラックホールが宇宙のどこでどうにどのように形成されたのかは、まだはっきりしていない。その起源の候補として、大質量連星によって作られる連星起源論、球状星団や銀河核のような星の密な領域で力学的な捕獲によって作られる捕獲起源論、宇宙初期に生成された原始ブラックホール同士が合体するという原始ブラックホール説などが提唱されている。

我々は、質量比の比較的大きい連星ブラックホール合体GW190412に注目して、このような天体が連星起源說から形成可能かどうかを調べた。この天体は質量比が4と大きくだけでなく、軌道角度運動量方向に描かれたブラックホールスピンも有限の大きさを持っていることがわかった。これらの性質が連星進化の過程、特に潮汐効果の結果として現れるのかどうかについて宇宙の星形成史および金属量の進化を考慮に入れた計算を行った。その結果、質量比が4ほどの場合、10-20%の連星合体は有限のスピンを持つ合体に至ることを示した。
11.1.3 超新星爆発におけるミュー・タウニュートリノ加速の研究

超新星爆発では大量のニュートリノが放出される。実際、大マゼラン雲で起こった超新星爆発1987Aでは、カミオオさんが10数個のニュートリノが検出された。現在、移動しているスーパーカミオカンデやIceCubeも近くの将来を構成するハイポーカミオカンデでは銀河系内で超新星爆発が起これば1万から数10万個のニュートリノが観測できる。将来的に、そのような観測データから何ができるのか？という問いは超新星科学を進める上でも重要な課題である。

これまでの研究では、超新星ニュートリノは電子タイプのニュートリノ・反ニュートリノとそれ以外のタイプのニュートリノ、反ニュートリノとして、ミユータイプとタウタイプには違いが見られないとして研究が進められてきた。この仮定はミユータイプ・タウタイプはそれぞれ中性カレントを通じて超新星物質と相互作用するという前提では、非常に良い近似であるが、ニュートリノのエネルギーがミユオンの質量を超える100MeV程度以上といった高エネルギー領域ではニュートリノの荷電カレントによる相互作用が重要になる。我々は、超新星爆発において中性子星が形成された際に生じる衝撃波をミユータウニュートリノが伝わり得るかを確認するフィールド加速を示した。この結果、ミユータウニュートリノが100MeV以上まで加速され、ニュートリノスペクトルが極めてハードになることを発見した。このakovはボルツマン方程式に基づく数値シミュレーションでも見られていたが、モンテカルロ法を使うことによってより定性的にも定量的にも明確な説明を与えた。このような100MeV以上のニュートリノは将来の観測でも十分なターゲットであり、ミユー・ミューの間の総編が解けることによって観測されるニュートリノスペクトルに現れる影響を議論した。

11.1.4 銀河の化学進化における乱流拡散の研究

銀河の化学進化計算は通常、銀河を一つの箱として考え、one-zone的な計算と銀河の成長などを一次元流体シミュレーションで解くという方法が用いられる。特に、連星中性子星合体が生成するR過程元素の化学進化を考える上ではそのイベントレートが低いため、one-zone的な近似はされ、銀河の非一様性を考える必要がある。銀河を空間的に分解する手法が必要である。そこで我々は銀河の星間物質中の重元素の非一様性が乱流拡散によって発展するという問題をモンテカルロ的に扱う方法を開発した。さらに、これまで観測されている銀河の星間物質の構成や太陽系の隣接などに記憶されている原始太陽系に含まれていた放射性重元素の量などの分布をこの手法で適用した。その結果、重元素は中性子星合体のような極めて稀な現象、具体的には銀河系で10万年に1度しか起こらない現象によって生成されたという視点によって非常にうまく説明できることを示した。今後、この手法によって、one-zone的な簡単な研究と流体シミュレーションなどのコストの高い研究との橋渡しが可能になる。

11.2 業績リスト

＜報文＞

(原著論文)


＜学術講演＞

(国際会議)

招待講演


(国内会議)
招待講演

(セミナー)