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変革を駆動する先端物理・数学プログラム（FoPM）
国外連携機関長期研修　報告書

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Background
Black holes provide some of the most extreme environments in the universe. Their growth and activity are believed to play a crucial role in the evolution of galaxies (e.g., Magorrian et al. 1998). Additionally, the strong gravitational fields near black holes provide an excellent testing ground for general relativity. Understanding black hole accretion systems is essential for studying both black hole growth and gravity theories. In black hole accretion systems, matter from the surrounding environment falls into the black hole through an accretion disk, releasing energy and producing intense radiation. X-rays emitted from the hot regions near black holes have been widely observed. However, the formation mechanisms and geometry of the hot gas, known as the "corona," which is believed to be the primary source of X-rays, remain uncertain. This presents a significant challenge in understanding the physics of accretion systems. Since different formation mechanisms predict different corona geometries, determining the geometry of the corona is a key step toward understanding its origin. In particular, developing models that can consistently explain both X-ray spectra and polarization observations may help reveal the physical properties of the corona. Additionally, understanding the corona geometries is crucial for measuring the black hole spin and testing general relativity using X-ray spectra.

Purpose
I stayed at the Harvard-Smithsonian Center for Astrophysics (CfA) for three weeks and spent a week at Arizona State University to attend the XRISM Science Team Meeting. The primary objectives of my research during my stay were as follows:

1. Developing of a Monte Carlo simulation code incorporating general relativistic effects.
2. Constructing of corona models in black hole accretion systems.
3. Discussing high-resolution X-ray spectroscopy.

Research
I stayed at the CfA for three weeks. At the CfA, researchers frequently gather for discussions during coffee breaks and lunchtime, creating an environment that encourages active idea exchange. My desk was in a shared office with other students working on X-ray observational data analysis, including the timing analysis of black hole binaries and the application of artificial intelligence (AI) to astronomical data analysis. These daily interactions provided a valuable opportunity to broaden my perspective and gain insights from researchers with diverse expertise.

During my stay, I presented a seminar on the development of MonacoGR, a Monte Carlo simulation code that incorporates general relativistic effects. In this seminar, I shared the current development status of MonacoGR and outlined future application plans. Following the presentation, I engaged in discussions with the audience. One researcher, who studies black hole spin evolution in active galactic nuclei (AGN), expressed interest in my work, and we explored the potential applications of MonacoGR for measuring supermassive black hole spin. Additionally, I implemented several functions in MonacoGR to support the modeling of the hot flow in accretion systems, as described in the following section. These improvements are expected to make the simulation more flexible and applicable to a wider range of astrophysical scenarios.

I constructed a preliminary corona model for black hole accretion systems. In this model, the properties of the corona are determined in a self-consistent manner by considering the energy balance between the corona and the accretion disk. By varying parameter values, I simulated the resulting X-ray spectra and polarization. I discussed the simulation outputs and potential model improvements with Dr. Steiner and his team members, receiving valuable feedback from both observational and theoretical perspectives. Their suggestions included refining certain assumptions about energy transfer mechanisms and incorporating additional observational constraints to make the model more realistic.

Additionally, I attended a meeting on the application of AI to astronomy. During the discussion, I exchanged ideas on the feasibility of using machine learning to improve MonacoGR simulations. We examined how and where machine learning models could replace full ray-tracing simulations to improve computational efficiency. I also visited the Black Hole Initiative (BHI), located near the CfA building, to discuss theoretical models of hot flows in black hole accretion systems. BHI is an institution dedicated to the study of black holes. Through discussions with researchers at BHI, I deepened my understanding of hot flow models, the sandwich corona model, and disk truncation mechanisms. These discussions helped me refine my approach to modeling black hole coronas. Additionally, I learned about recent theoretical developments related to jet formation and their possible connection to corona dynamics.

I attended the XRISM Science Team Meeting at Arizona State University. XRISM is a newly launched X-ray observatory (September 2023) with unprecedented energy resolution. The meeting brought together XRISM Science Team members from around the world to discuss high-resolution X-ray spectroscopy using XRISM data. This event provided a valuable opportunity to interact with experts in observational astrophysics and gain insights into the latest data analysis techniques.

At the meeting, I exchanged opinions with team members on the analysis of performance verification (PV) data. The energy resolution of XRISM spectra is significantly higher than that of previous X-ray satellites. Consequently, to analyze XRISM data accurately and maximize its potential, we must account for certain effects that were negligible in past analyses. During discussions, we identified key considerations for XRISM high-resolution spectroscopy. I also discussed the general relativistic effects expected to be observed with XRISM. This involved discussions on GR ray-tracing codes, corona structure and origin scenarios, and the relationship between XRISM spectral features and jet phenomena or multi-wavelength observations. Furthermore, we deliberated on future observational and analysis plans aimed at unveiling the structure surrounding black holes.

Overall, my stay at CfA and participation in the XRISM Science Team Meeting were highly productive. I gained valuable feedback on my research, deepened my understanding of black hole accretion physics, and established new collaborations that will contribute to future studies. The insights and connections formed during this period will be instrumental in further developing MonacoGR and refining our models of black hole coronae.