Statement of Purpose

Aryan Bhake (Astrophysics PhD for Fall 2025)

I am excited to express my strong interest in pursuing a **PhD position** at ISTA, Austria. My background in high-energy astrophysics and computational modelling aligns closely with the research focuses of the **Astrophysics groups led by Haiman, Gotberg and Matthee**and I am particularly enthusiastic about contributing to the cutting-edge investigations conducted by these teams.

My thesis at the Indian Institute of Technology, Indore, under Dr. Bhargav Vaidya, centers on "Numerical Modelling of Binary Black Hole (BBH) Dynamics Embedded in Active Galactic Nuclei (AGN) Discs." Using the shock-capturing Godunov-type finite volume **PLUTO** code, I explore the effects of angular momentum transfer and magnetic fields on binary black hole evolution within AGN environments. We performed a suite of hi-resolution MHD simulations to extract an electromagnetic (EM) signal from the BBH merger. We also intend to investigate the inspiral phase especially the transition from gas driven orbital decay to gravitational radiation dominated orbital decay and generate its corresponding GW waveform using SEOBNR/CBwaves codes. This would enable us to get a prediction and co-relation between a GW signal and its EM counterpart. This project has given me a solid foundation in numerical relativity especially Post-Newtonian, Post-Minkowskian theory and the effective one-body (EOB) formalism, as well as a deep appreciation for how computational models can help understand complex astrophysical processes in high energy, magnetized settings. Up until now not many studies have been done on the surroundings of a merger and how it affects the GW signal, I believe I can contribute significantly to fill this gap. With this project I have developed a robust proficiency in programming languages such as C/C++ and Python which will be beneficial for the research objectives of the PhD position. I have also presented my research at notable conferences, including the 33rd meeting of the Indian Association for General Relativity and Gravitation (IAGRG) hosted at BITS Pilani. More technical knowledge was gained when during my coursework I took a course in 'Computational methods for Astronomy' where I learnt CFD and 'Astrostatistics' where I learned about MCMC and used the Metropolis-Hastings algorithm to estimate cosmological parameters using SNe-Ia data.

Beyond my thesis work, I have led and contributed to several other research projects that have provided me with a strong theoretical and computational foundation in astrophysics. One significant project was my study titled "Possible relations between Fast Radio Burst (FRB) and Gamma Ray Bursts (GRB)" where I investigated emission mechanisms behind FRBs and GRBs. This study was a deep dive into synchrotron shock models, exploring the variability in synchrotron emission from relativistic jets and the conditions that enable shock acceleration within these extreme environments. In another project, titled "Comparative Study of Pulsars Based on Emission Mechanisms," conducted in collaboration with Dr. Sunder MN and the SSERD group, I undertook a comprehensive analysis of pulsar emission models. This study aimed to explore how emission properties vary across pulsars with different environmental and intrinsic characteristics. To achieve this, we used data from the ATNF Pulsar Catalogue and SIMBAD to extract pulsar parameters across multiple frequencies and developed a data extraction pipeline in Python to retrieve and preprocess the necessary datasets.This experience not only deepened my understanding of pulsar astrophysics but also provided me with valuable skills in data handling and statistical analysis, which are crucial for any data-intensive research.

During my bachelor's dissertation, under Dr. Abhijeet Borkar at the Astronomy Institute of the Czech Academy of Sciences, I analyzed the Fundamental Plane (FP) of black hole activity, examining how black hole properties correlate with redshift and radio loudness. I used softwares like TOPCAT to cross relate data from VLA,SDSS and XMM-Newton. I wrote Python scripts for data reduction and sanitation. This project underscored the importance of empirical data in constructing models of astrophysical behavior and cemented my desire to pursue high-energy astrophysics.

My research interests align closely with the work of Professor Zoltán Haiman, whose pioneering efforts in understanding black hole formation, growth and their observational signatures inspire my academic pursuits. One area of great interest to me is the interaction between merging black holes and their surrounding circumbinary gas. Modelling these systems is essential for understanding how the gas influences the BBHs' orbital evolution and their gravitational wave emission. I am particularly fascinated by how these gas-driven effects manifest in observable gravitational wave signals which could provide critical insights into the astrophysical environments of these mergers. This project can be an extension of my ongoing Master's thesis and has a lot of potential for new physics. I am also interested in the rapid formation and growth of seed black holes in the early universe. Understanding the conditions that allow these black holes to grow quickly during the epoch of reionization has profound implications for explaining the observed population of supermassive black holes in the early universe. I aim to contribute to developing computational models and help in light-curve modelling to identify and distinguish the different pathways by which these massive black holes could form.

Dr. Ylva Götberg's work on the evolution and observational characterization of massive binary stars particularly the processes that lead to envelope stripping and the formation of helium stars is fascinating. Stripped stars are critical for understanding the ionizing radiation budgets of galaxies and play a key role in binary evolutionary pathways leading to phenomena such as mergers and GWs. I am interested in using population synthesis models, coupled with spectral synthesis tools, to predict the observable properties of stripped helium stars in various stellar environments. For example, I am eager to explore a project that combines multi-wavelength photometric surveys with synthetic spectra of stripped stars to identify candidates in local and high-redshift galaxies. This approach, alongside theoretical models of binary evolution, could shed light on the mechanisms driving envelope stripping and quantify their contribution to reionization.

Dr. Matthee's work on understanding galaxies as both tracers and agents of cosmic reionization is also very attractive. I am interested by the prospect of using H-alpha and O-III emission to quantify star formation rates and trace metal production in these galaxies which provides insights into their evolution and role in reionization, a project similar to this is already ongoing at my current institute hence I am somewhat familiar with the idea. A project that combines these emission line measurements with hydrodynamic simulations could reveal how ionizing radiation escapes from galaxies and propagates through the intergalactic medium.

Joining ISTA represents a unique opportunity to engage with a dynamic and interdisciplinary research environment, where leading experts like Professors Haiman, Götberg and Matthee are at the forefront of advancing our understanding of the universe. The collaborative and intellectually stimulating atmosphere at ISTA will provide the perfect foundation for me to contribute meaningfully to cutting-edge research in high-energy astrophysics, computational modellingand observational astronomy The collaborative nature of research at IIT Indore has prepared me well for such interdisciplinary and international environment. ISTA represents an ideal avenue to apply and develop new skills. I am enthusiastic about the possibility of joining the vibrant community at ISTA. Thank you for considering my application.