THE ANNUAL REPORT

Name and surname	Rafia Sarwar
Project title	Gamma-ray burst and gravitational-wave event rates: modern population synthesis
Scientific disciplines	Astronomy
Scientific Supervisor	Dr. Dorottya Szecsi
Assistant Supervisor	
Foreign scientific supervisor	

Year of study: (the academic year 2022/ 2023)

1. Description of the progress in the preparation of the doctoral dissertation and the progress in conducting scientific research

Project 1: Progenitors of LGRBs: Are single stars enough?

This annual report for the academic year 2022/2023 gives a comprehensive overview of the progress made towards achieving the scientific goals outlined in our research plan. Development of the FINFAT code (functionalities explained in Individual Research Plan) primarily requires investigation of metallicity-dependent cosmic star formation (CSF), application of CSF models to population synthesis results, and testing these models against observational data.

1. **First scientific goal:** Performing (single-star) population synthesis on the models from Yoon et al. (2006) [1]. The routines need to be developed in a way that later models (those computed with the MESA code later on) can be processed the same way. This will become the first cornerstone of the FINFAT code.

→ **Partly achieved.** Primary Goal: The central objective or focus of the research or project for the academic year 2023 was to create MESA models. That has been successfully achieved in collaboration with the post-doctoral group member Dr. Koushik Sen. He is an expert in stellar and binary evolution studies. MESA (single-star) models: MESA stands for Modules for Experiments in Stellar Astrophysics. MESA is an open source free computer-based model used in astrophysics to simulate and study the behaviour and characteristics of single and binary stars. During this academic year MESA models using the latest MESA version 23.05.1 have been created for varying masses from 10 – 100 $M_\odot$, range of rotational velocities 0.1 - 0.8 in units of Keplerian velocity for four different metallicities 0.01, 0.001, 0.0001, 0.00001 using appropriate astrophysical prescriptions. These evenly-spaced MESA models help us to accurately represent and predict the key properties for the evolution and fate of massive stars. These MESA models have been obtained in collaboration with post-doctoral researcher Koushik Sen in our group.

For further analysis, a grid of these single-star models has been created. A similar grid of Yoon's models has been used already been used last year as an initial test. Grid typically refers to a systematic set of data points or simulations that cover a range of values. We've developed an extensive collection of MESA models, encompassing mass combinations ranging from 10 to 100 $M_\odot$ and rotational velocities spanning 0.1 to 0.8 in Keplerian units, across four distinct metallicities: 0.01, 0.001, 0.0001, and 0.00001. These models are used to explore how these parameters influence the evolution and fate of massive stars.

After creating the grid of MESA models, a thorough analysis was done successfully. This analysis involves comparing the model predictions to previously obtained Yoon's data to ensure their accuracy and reliability. Any discrepancies or issues are carefully examined and revised.

Having successfully generated and analyzed MESA models for individual stars, we are now prepared to undertake population synthesis. This entails applying the appropriate initial mass function and velocity distribution, and we plan to integrate results from both MESA and Yoon's grids for our first paper.

Furthermore, starting this month, biweekly meetings for the development and analysis of binary stellar models will be initiated with Dr. Poojan Agrawal, a MESA expert from the University of North Carolina, USA. This collaboration is expected to facilitate the exchange of knowledge, rigorous analysis, and access to additional resources, promoting innovative advancements in this PhD project.

2. Second scientific goal: Investigating the issue of metallicity-dependent cosmic star-formation (CSF), and applying various CSF-models to the population synthesis results (mentioned above). This will become another cornerstone of the FINFAT code.

→ **Partly achieved.** The goal of investigating metallicity-dependent cosmic star formation (CSF) and integrating various CSF models has been partly achieved. At the moment, the comprehensive study and analysis of different metallicity-dependent CSF models, drawn from both observational data and theoretical models, has been done.

This examination includes seminal works such as those by Madau & Dickinson (2014), Madau & Fragos (2017), Strolger et al. (2004), Neijssel et al. (2019), and Buisson (2020). Additionally, various mass-metallicity (MZ) relations, as outlined by Tremonti (2004), Savaglio (2005), Langer (2006), Ma et al (2015), bisector fit of Savaglio et al. (2005) and Savaglio et al. (2005), have been scrutinized alongside Galaxy Stellar Mass functions (GSMF) utilizing Schechter and Double Schechter functions. This research builds upon the approach established by Neijssel et al. 2019. In the next step, all of these CSF models and mass-metallicity relations will be integrated with a Monte-Carlo simulation to predict properties of our synthetic population for long-duration gamma-ray bursts for single star models and then extend this treatment for binaries.

3. Third scientific goal: Testing the various CSF models against the observational dataset (completed in Year I).

→ **Initiated.** Currently, I am in the process of developing code that integrates CSF models with our synthetic population. In other words, the assessment and validation of these models against real-world observational data will be conducted as the next step because the CSF models necessitate further development and refinement before they can be effectively tested and validated against the existing dataset.

4. Fourth scientific goal: Finishing a complete draft of the paper (see Year I).

→ **Initiated.** The fourth scientific goal, which is to finalize a comprehensive draft of the paper, as outlined in Year I, has been initiated. Conducting a thorough analysis of the integrated MESA models alongside the cosmic star-formation (CSF) is now being prepared for scientific publication. While the initial draft has been initiated, its completion requires additional time and the incorporation of further results to ensure the paper is thoroughly substantiated and ready for submission.

Project 2: Quantitative Predictions for Ultra-Long Gamma-Ray Burst Progenitors

This research project represents a valuable collaboration with our esteemed local colleague, Mariusz Tarnopolski, a winner of the SONATA grant. This collaboration not only exemplifies our commitment to fostering great collaborations within our close-knit group but also showcases our broader engagement with the Institute of Astronomy and the Piwnice Astronomical Observatory.

Our joint focus is on exploring the fascinating realm of massive stellar progenitors with low-metallicity and rapid rotation. In particular, we are studying in detail the core-collapse stage of stellar models that challenge the conventional Long Gamma-Ray Bursts (LGRB) scenario due to the presence of an unusually extended envelope. This extended envelope leads to an accretion timescale that significantly exceeds the typical association with LGRBs. Furthermore, the presence of this extended envelope not only challenges the conventional collapsar scenario but also raises the intriguing possibility of ultra-long gamma-ray bursts (ULGRBs).

ULGRBs represent a distinct class of astrophysical events characterized by exceptionally prolonged duration and different angular momentum dynamics as compared to LGRBs. Understanding the potential occurrence of ULGRBs is a key aspect of our research. Thus more precise quantitative predictions necessitate the generation of extensive grids of massive star models, varying in mass, metallicities and rotational velocities, accounting for fine resolutions in the initial rotation rate parameters. These predictions must also consider appropriate initial functions for various stellar parameters. Scientific Goals: These scientific goals collectively contribute to a deeper understanding of stellar evolution, the dynamics of GRB formation, and potential connections between different types of GRBs.

Scientific goals:

1. First scientific goal: Investigate density distributions and free fall time scales at specific stages of stellar evolution, specifically at the end of the core carbon-burning phase and the end of the core iron-burning phase, utilizing the models developed by Perna et al. (2018).

→ **Successfully achieved.** The research delved into specific phases of stellar evolution, focusing on the end of the core carbon burning phase and the end of the core iron burning phase. This investigation was carried out using the comprehensive models developed by Perna et al. in 2018. The study involved a detailed examination of density distributions and free fall time scales at these critical stages, shedding light on the dynamics of massive stars during their evolutionary journey.

2. Second scientific goal: Apply the obtained results to the analysis of MESA models, building upon the models created during the academic year I. Initially, the analysis was based on Yoon's models, but it has since expanded to use the new MESA grids.

→ **Successfully achieved.** The analysis progressed from the initial use of Yoon's models to incorporating more recent MESA (Modules for Experiments in Stellar Astrophysics) grids. Building on findings at earlier stages of the project, the analysis expanded to include MESA models. This transition enabled a more detailed and robust exploration of evolving stellar systems, significantly increasing the accuracy of this research.

3. Third scientific goal: Separate and scrutinize models that evolve chemically homogeneously from the overall grid. Focus on detailed statistical analysis and checks, particularly on models where the specific angular momentum of a star at the end of the core carbon burning phase exceeds that of an accretion disk corotating with a black hole at its last stable orbit, relevant to the production of GRBs.

→ **Successfully achieved.** A key aspect of this project involved isolating and meticulously scrutinizing models that undergo chemically homogeneous evolution within the broader grid of stellar models. This in-depth analysis focused on specific criteria, particularly scenarios where the specific angular momentum of a star at the end of the core carbon burning phase surpassed that of an accretion disk corotating with a black hole (BH) at its last stable orbit. This investigation was highly relevant to the production of GRBs, providing crucial insights into the mechanisms behind these high-energy astrophysical events.

4. Fourth scientific goal: Explore potential connections between ULGRBs and LGRBs, particularly investigating if ULGRBs, which require slightly slower initial rotation rates, can be produced through this alternative channel.

→ **This will be continued next year.**

5. Fifth scientific goal: Produce detailed quantitative forecasts by systematically varying critical parameters, including stellar mass, metallicity, and rotational velocity, to elucidate their potential roles as progenitors of Ultra-Long Gamma-Ray Bursts (ULGRBs). Subsequently, integrate these predictions with observational data to establish empirical correlations and validate the theoretical framework for future potential projects.

→ **This will be continued next year.**

In summary, the research accomplished several objectives, advancing our understanding of stellar evolution, the dynamics of massive stars at critical phases, and their potential role in the production of GRBs. The seamless transition from initial models to more refined MESA grids, along with the detailed examination of chemically homogeneous evolution, collectively contribute to the broader scientific understanding of these complex astrophysical phenomena.

References:

[1] S.-C. Yoon, N. Langer, C. Norman, Astronomy & Astrophysics, Volume 460 (1) 199-208, 2006.

[2] Madau P., Dickinson M., Astronomy & Astrophysics, Volume 460, 415, 2014.

[3] Madau P., Fragos T., 2017, ApJ, 840, 39

[4] Strolger L.-G. et al., 2004, ApJ, 613, 200

[5] Neijssel C. J., et al., 2019, MNRAS, 490, 3740

[6] du Buisson L., et al., 2020, MNRAS, 499, 5941.

[7] Tremonti C. A. et al., 2004, ApJ, 613, 898

[8] Savaglio S. et al., 2005, ApJ, 635, 260

[9] Langer N., Norman C. A., 2006, ApJ, 638, L63

[10] Ma X et al., 2016, MNRAS, 456, 2140

[11] Savaglio S. et al., 2005, ApJ, 635, 260

[12] Langer N., Norman C. A., 2006, ApJ, 638, L63

[13] Perna R., Lazzati D., Cantiello M., 2018, ApJ, 859, 48

2. Participation in classes

[Title of courses, amount of hours, ECTS credits].

1. Name of the course: Ethics and Intellectual Property
   Course code on USOS: 7405-AC-EIP-2
   Form of classes: Lecture
   Final grade: 4
   Number of hours: 10 hours
   Number of ECTS points: 1.00 ECTS credit

2. Name of the course: History of Scientific Thinking and Inquiry
   Course code on USOS: 7405-AC-HST-2
   Form of classes: Lecture
   Final grade: 5
   Number of hours: 10 hours
   Number of ECTS points: 1.00 ECTS credit

3. Name of the course: Artificial Intelligence and the Future of Scientific Thinking
   Course code on USOS: 7405-AC-AI-2
   Form of classes: Lecture
   Final grade: 5
   Number of hours: 10 hours
   Number of ECTS points: 1.00 ECTS credit

4. Name of the course: Evolutionary biology
   Course code on USOS: 7405-AC-EB-2

Form of classes: Lecture
Final grade: Exam is scheduled on 18th of September 2023
Number of hours: 10 hours
Number of ECTS points: 1.00 ECTS credit

5. Name of the course: Supervisory mentoring
   Course code on USOS: 7405-AC-SMEN-1
   Form of classes: Promoter mentoring
   Final grade: 4.5
   Number of ECTS points: 4 ECTS credit

6. Name of the course: Scientific Data Presentation and copyright II
   Course code on USOS: 7405-AC-SDPC2-2
   Form of classes: Seminar
   Final grade: 4.5
   Number of hours: 10 hours
   Number of ECTS points: 1.00 ECTS credit

7. Name of the course: Elements of Occupational Health and safety and Ergonomics
   Course code on USOS: 9001-BHP-5-SD
   Form of classes: Exercises
   Final grade: ZAL
   Number of hours: 5 hours
   Number of ECTS points: lack

3. Participation in scientific conferences.

[name of conference, organiser, dates]

1. Workshop title: Best grant opportunity for new postdocs. How to successfully apply for Marie Skłodowska-Curie postdoctoral fellowship?
   Date: 19 - 20 October 2022
   Venue: Nicolaus Copernicus University, 87-100 Toruń, Poland.

2. Conference name: 16th annual meeting of the VLT-FLAMES Tarantula Survey (VFTS) collaboration
   Date: 27 - 29 March 2023
   Type of participation: Poster presentation (Title: Progenitors of LGRBs: Are single stars enough?) (Online participation)
   Venue: MPA, Garching, Germany.

3. Conference name: European Astronomical Society Annual Meeting
   Date: 10 - 14 July 2023
   Type of participation: Poster and oral presentation (Title: Progenitors of LGRBs: Are single stars enough?)
   (Category of Symposium LS15: Magnetars as central engines across the Universe, EAS 2023)
   Venue: Kraków, Poland.

4. Conference name: Massive Triples, Binaries and Mergers 2023
   Date: 17-21 July 2023
   Type of participation: Online participation only
   Venue: Leuven, Belgium.

4. Internship. [Name of the institution, place, dates, description of the internship]. Not applicable
5. Initiating a doctoral assessment process – yes/no [delete as appropriate]. Not applicable
6. Submission of the doctoral dissertation – yes/no [delete as appropriate]. Not applicable
7. Teaching practice Not applicable
8. Applying for a research grant. The *University Center of Excellence for “Astrophysics and Astrochemistry”* fully funds this PhD position for four years with a generous amount including all the expenses for foreign business trips to participate in conferences, workshops and summer/winter schools. Therefore, applying for an additional research grant is not necessarily required at this stage of doctoral studies.

13 - 09 - 2023
Date

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PhD student’s signature

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Scientific Supervisor’s signature

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Signature of the Head of ISD AC