NICOLAUS COPERNICUS UNIVERSITY IN TORUŃ

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 2023/ 2024)

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 2023/2024 academic year presents a comprehensive overview of my progress toward the scientific goals outlined in my research plan. As detailed in the plan, the research focuses on investigating the metallicity dependence of cosmic star formation (CSF), using CSF stellar model grids for population synthesis and validating models of rapidly rotating massive stars compared to the observational data.

Scientific goals:

1. **First scientific goal:** Performing single-star population synthesis using the models from Yoon et al. (2006). Additionally, compute an extended MESA (Modules for Experiments in Stellar Astrophysics) grid of stellar models (Paxton et al. 2011, 2013, 2015, 2018, 2019; Jermyn et al. 2023), focusing on improved metallicity resolution for the first paper.

   → Successfully achieved. Performing single-star population synthesis using the models from Yoon et al. (2006). Additionally, compute an extended MESA (Modules for Experiments in Stellar Astrophysics) grid of stellar models (Paxton et al. 2011, 2013, 2015, 2018, 2019; Jermyn et al. 2023), focusing on improved metallicity resolution for the first paper. The primary focus of the research over the past two academic years was the development of MESA models, completed in collaboration with Dr. Koushik Sen, an expert in stellar and binary evolution. MESA, is an open-source software extensively used in stellar astrophysics for simulating the behaviour of single and binary stars. Last year, we created MESA models using version 23.05.1, covering mass ranges from 10 to 100 $M_\odot$ and rotational velocities from 0.1 to 0.8 (in Keplerian units) across four different metallicity: 0.01, 0.001, 0.0001, and 0.00001. These single star models showed.

2. **Second scientific goal:** Analyze these MESA stellar evolution models thoroughly. Study the variations in properties such as mass, radius, and specific angular momentum at both the core and stellar surface boundary across all seven metallicities.

   → Successfully achieved. As mentioned above, I have successfully achieved our scientific objective by extending the grid to encompass all seven metallicities: 0.017 (solar), 0.01, 0.004 (LMC), 0.002 (SMC), 0.001, 0.0001, and 0.00001.

   This scientific goal has been completed by thoroughly analyzing MESA stellar grids. We examined the variations in properties such as mass, radius, and specific angular momentum at the core and the stellar

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surface boundary for all seven metallicities. These findings provide clear insights that allow us to differentiate between stellar models evolving chemically homogeneously (CHE) and those evolving normally (NE) (Maeder 1987, Heger et al. 2003, Hirschi et al. 2005, Yoon & Langer 2005, Yoon et al. 2006, Brott et al. 2011, Ekström et al. 2012, Maeder & Meynet 2012, Szecsi 2017, Obergaulinger & Aloy 2017, Aguilera-Dena et al. 2018, Aloy & Obergaulinger 2021, Roy 2021, Li et al. 2023).

Overall, my new MESA grids includes stellar mass ranging from 10 to 100 solar masses and rotational velocities ranging from 0.1 to 0.8 in Keplerain units, covering a wide range of metallicities: 0.017 (solar), 0.01, 0.004 (LMC), 0.002 (SMC), 0.001, 0.0001, and 0.00001. These models enable us to study how these properties impact the evolution and final outcome of massive stars.

After creating the MESA stellar model grids, we conducted a detailed analysis, comparing our predictions with results of Yoon et al. (2006) to ensure consistency and accuracy. Having completed the evolution and analysis of individual stellar models, I again performed population synthesis to the extended stellar models. This involved applying an initial mass function and velocity distribution. Metallicity-dependent cosmic star formation (CSF) across an extensive grid of all seven metallicities has been successfully accomplished (van Son et al. 2023 and references therein). I also conducted a thorough study and analysis of various CSF models that are sensitive to metallicity, incorporating insights from both observational data (https://www.mpe.mpg.de/~jcg/grbgen.html) and theoretical frameworks.

The next phase involves integrating different CSF models (Neijssel et al. 2019, Chruslinska & Nelemans 2019, Boco et al. 2021, Chruslinska et al. 2021) and mass-metallicity relations (Tremontiet al. 2004, Savaglio S. et al. 2005, Langer & Norma 2006, Ma et al. 2015, Savaglio et al. 2005 and Savaglio et al. 2005) with a Monte Carlo simulation to predict the properties of our synthetic population of progenitors of long-duration gamma-ray bursts (LGRBs). This will be detailed in our upcoming publication, in which I compare the theoretical predictions of the observed number of LGRBs with known redshifts (https://www.mpe.mpg.de/~jcg/grbgen.html), I showed that the revised massive-star physics, particularly the improved treatment of mass loss from stellar winds during evolution (Brott et al. 2011), provides a more accurate explanation of the observed LGRB distribution than previous theoretical models.

3. **Third scientific goal:** Testing various input physics against the observational data, drawing conclusions about why some input physics explains the observations better than others. e.g. why a top-heavy initial mass function or a modified rotational-velocity distribution works better, or running *MESA* models with modified internal mixing processes (rotational mixing efficiency, semi-convection, magnetic fields can be tested here, amongst other things).

   → **Not achieved.** The scientific objective of testing various input physics against observational data and determining why certain models better explain the observations, such as different initial mass functions or a modified rotational-velocity distribution, has not been fully achieved. Similarly, the exploration of MESA models with altered internal mixing processes—such as rotational mixing efficiency, semi-convection, and the influence of magnetic fields—remains incomplete. As a result, this goal has been extended to the next year for further investigation and refinement in the next year.

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

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

   → Partly achieved.

   → **Collaboration with Christina Thöne to look into the observational analysis and biases.**

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

Project 2: Explain the Skewness in the Gamma-Ray Burst Duration Distribution using progenitor stars.

In this project, we examine the core-collapse phase of stellar models that differ from the standard LGRB scenario due to the presence of extended envelopes in the NE stars. In contrast, CHE stars and stripped envolope stars lose their outer layers over time, resulting in compact radii at the time of core-collapse and shorter free-fall timescales (Massey 1981, Cherepashchuk & Postnov 2001). This extended envelope leads to an accretion timescale longer than what is typically associated with LGRBs. These varying timescales could lead to a skewed distribution of the duration T90— the time during which 90% of the total energy of a GRB is detected — which was previously investigated by (Tarnopolski 2015, Zitouni et al. 2015, Tarnopolski 2016).

Scientific goals:

1. **First scientific goal:** Investigate density distributions and free fall time scales at end of carbon burning phase of stellar evolution

   → Successfully achieved. This goal focused on examining stellar radii, specific angular momentum and density distributions and free fall time scales during the last stages of stellar evolution, particularly at the end of the core-carbon burning and core iron burning stages. I successfully conducted a detailed analysis of these phases, improving our understanding of massive star evolution.

2. **Second scientific goal:** Analyze MESA models using results from previous work

   → Successfully achieved. After successfully achieving the scientific goals of this project in the previous year, we now use our extended grids from the first project, incorporating MESA models using version 23.05.1. This grid covers mass ranges from 10 to 100 solar masses and rotational velocities from 0.1 to 0.8 (in Keplerain units) for four different metallicities 0.01, 0.001, 0.0001, 0.00001. Likewise **project 1**, I expanded the stellar grids by adding three additional metallicities: 0.017 (solar), 0.004 (Large Magellanic Cloud), and 0.002 (Small Magellanic Cloud), while maintaining the same mass and velocity ranges. We calculate the free fall time scale and revise computations done in academic year 2022-2023 with the extended stellar model grids.

3. **Third scientific goal:** Perform detailed sanity checks on key models

   → Partly achieved. A crucial part of this project involved performing detailed sanity checks on models with specific angular momentum exceeding that of an accretion disk. This in-depth analysis confirmed the consistency and accuracy of our stellar models under study, further confirming their relevance to the production of LGRB and expanding our understanding of the late stages of stellar evolution.

   → This will be continued next year.

4. **Fourth scientific goal:** Finishing a complete draft of the paper.

   → Partly achieved.

   → This will be continued next year.

In summary, I successfully accomplished most of the objectives of this academic year, advancing our understanding of stellar evolution, the dynamics of massive stars at critical phases, and their potential role in the production of LGRBs. The improvement from initial stellar model grids to extended MESA grids, along with the detailed study of

CHE, collectively contribute to the broader scientific understanding of these progenitors of LGRBs.

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2. Participation in classes

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

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

2. Name of the course: Successful grant application
   Course code on USOS: 7405-AC-SGA-1
   Form of classes: Lecture
   Final grade: 4
   Number of hours: 10 hours
   Number of ECTS points: 1.00 ECTS credit

3. Participation in scientific conferences.

[name of conference, organiser, dates]

1. Workshop title: Stable Mass Transfer in Binaries: from onset to remnants
   Date: 11 - 13 March 2024
   Venue: CCA, Flatiron Institute, 162 5th Ave. New York, US.

2. Workshop title: VLT-FLAMES TaranTula Survey Conference
   Date: 16 - 18 September 2024
   Venue: European Space Astronomy Centre (ESAC), Villanueva de la Cañada, Madrid.

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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.

24 - 09 - 2024
Date

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PhD student's signature

....
Scientific Supervisor's signature

Dyrektor
Interdyscyplinarnej Szkoły Doktorskiej
"Academia Copernicana"
I accept
prof. dr hab. Iwona Kałużyńska
....
Signature of the Head of ISD AC