NICOLAUS COPERNICUS UNIVERSITY IN TORUŃ
Doctoral Schools

RESEARCH UNIVERSITY
EXCELLENCE INITIATIVE

THE ANNUAL REPORT

Name and surname	Mgr Rafia Sarwar
Project title	Gamma-ray burst and gravitational-wave event rates: modern population synthesis
Scientific disciplines	Astronomy
Supervisor	Dr. hab. Dorottya Szécsi, prof. UMK

Year of study: the academic year 2024/2025

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?

The annual report for the academic year 2024/2025 summarises the scientific progress made in the projects and objectives listed in the individual research plan. Last year (2023/2024), it mainly focused on the development and extension of the MESA-based stellar evolution model grids for a wide range of initial masses, rotational velocities, and metallicities [initial masses from 10 to 100 solar masses, rotational velocities between 0.1 and 0.8 in Keplerian units, and metallicities ranging from solar (Z = 0.017) down to Z = 0.00001]. These stellar grids were then used as input for population synthesis runs, adopting different prescriptions for the initial mass function (Salpeter 1955; Kroupa 2001; Chabrier 2003), rotational velocity distributions (Yoon, Langer & Norman 2006, Ramírez-Agudelo et al. 2013), and cosmic star formation models (Hopkins & Beacom 2006; Madau & Dickinson 2014). This year, the progress was focused on the statistical interpretation of observational datasets, carefully examining observational biases, and writing a substantial portion of the first research paper. This marks a transition from constructing theoretical models to comparing theory with available observational datasets. During this process, I compared open-source datasets of long-duration gamma-ray bursts (LGRBs). Specifically, I considered the Caltech GRBox database of observed GRBs (https://sites.astro.caltech.edu/grbox/grbox.php?starttime=700101&endtime=181231) alongside the MPA Garching GRB catalogue (https://www.mpe.mpg.de/~jcg/grbgen.html). Through detailed cross-checking of these datasets, I concluded that the latter is essentially a subset of the former and is regularly updated each month. This analysis allowed me to replace the GRBox dataset to the MPA Garching GRB catalogue as the baseline dataset for population studies of LGRBs, given that the MPA Garching dataset is more complete and reliable. Such dataset comparisons are essential to identify the selection effects and observational biases that complicate the inclusion of data in the GRB catalogues and their use in population synthesis (Strolger et al. 2004; Butler et al. 2007; Wanderman & Piran 2010). During data analysis, I recognised that observational incompleteness is not only related to missing redshifts but also correlates with instrumental sensitivity and follow-up spectroscopic challenges (Jakobsson et al. 2006; Hjorth et al. 2012). To investigate this further, I collaborated with *Dr. Christina Thöne* and engaged in detailed discussions about observational biases, which I subsequently included in a dedicated section of the paper, specifically addressing flux thresholds in detectors like Fermi and Swift (Gehrels et al. 2004; Meegan et al. 2009). Selection effects related to metallicities comes from the fact that GRBs are more frequently found in low-metallicity host environments (Savaglio et al. 2005; Langer & Norman 2006; Perley et al. 2016). I constructed figures of redshift distributions to illustrate these detection biases and wrote a detailed discussion section in paper draft about the origin of observational and astrophysical biases within the context of metallicity-dependent cosmic star formation histories (Madau & Fragos 2017; Robertson & Ellis 2012).

Writing the first major research paper took up most of this year's time, particularly with the progress made in writing the methods section [a comprehensive description of the stellar grids constructed with MESA (Paxton et al. 2011; Paxton et al. 2013; Paxton et al. 2015; Paxton et al. 2018; Paxton et al. 2019)] and results sections. These results include detailed sections on Hertzsprung–Russell (HR) diagrams at solar metallicity, highlighting the three evolutionary pathways of normally evolving stars (NE), transitionally evolving stars, and chemically homogeneous evolution (CHE). This discussion explains how the selection of initial metallicity and rapid rotation influences the structural evolution of massive stars (Brott et al. 2011; Yoon et al. 2006). In this paper, I also include a detailed analysis of the internal stellar structures that result in varying core radii, rotational mixing efficiencies, and angular momentum transport at the end of the stellar evolution. All these properties, such as compactness parameters (O'Connor & Ott 2011; Ertl et al. 2016) and distributions of specific angular momentum at the end of the carbon-burning phase (Perna, Lazzati & Cantiello 2018; Aguilera-Dena et al. 2020), are primarily important to characterise and distinguish progenitors capable of retaining sufficient core specific angular momentum for collapsar formation (Maeder 1987; Heger et al. 2000; Langer 2012) and most likely forming relativistic jets associated with LGRBs (Woosley 1993; Woosley & Heger 2006). During this year, I also created plots of cumulative distribution functions (CDFs) of the observed LGRB redshift distribution (MPA datasets, also known as Jochen Greiner's GRB dataset) and compared them with MESA-based synthetic populations of LGRB progenitors, applying mass-metallicity relations (Tremonti et al. 2004; Ma et al. 2015) and metallicity-dependent cosmic star formation histories (Neijssel et al. 2019; Chruslinska & Nelemans 2019; Boco et al. 2021; Chruślińska et al. 2021; Langer & Norman 2006; van Son et al. 2023).

In our original individual research project plan, we anticipated moving toward binary progenitor models. This expectation was motivated by initial results from Year-I, where a preliminary comparison (e.g., Yoon et al. 2006 vs. GRBbox) suggested that some relevant physics might be missing, which we tentatively associated with binarity.

However, before going on to the complex binary stellar models, we considered it essential to first fully explore the single-star models and all relevant physics was properly taken into account. We found that already within the single-star framework, we can reproduce a good fit to the observed LGRB population. This result is sufficiently encouraging that we decided to improve our understanding of single stars, rather than shifting to binaries.

This does not implies that binaries are unimportant or irrelevant. Also, we are aware of their clear role as potential contribution to LGRB production. Instead, our approach is indicative of a logical progression. This includes good understanding of the single-star contribution first, and then, proceed to the next step, incorporating binary evolution in future work. Thus, the present thesis focuses on detailed explaination of the single-star scenario.

Scientific goals:

1. **First scientific goal:** Test single stellar population models against the LGRB data, and interpret the results critically. Draw conclusions and discuss their implications in the paper draft.

   → **Successfully achieved.** The focus of this year was to use the MESA stellar models already created in the previous years. I successfully tested single stellar population models against LGRB data and critically interpreted the outcomes. This comparison show that updated input physics in MESA models are consistent with the observed LGRB redshift distributions. These results were then used to draw conclusions about that CHE is leading pathway to produce progenitors of LGRBs.

   → **Ongoing and this will be continued next year.** I wrote all these findings in a paper draft. The draft of the single-star evolution paper is complete, including detailed methods, results, figures, and statistical comparisons with earlier studies. A major focus in 2025 was the inclusion of observational constraints to the paper, which has now been achieved. The draft is currently under active revision with input from supervisors and collaborators, and will undergo a few more rounds of editing before the final submission.

2. **Second scientific goal:** Finish writing the PhD thesis by completing the Introduction and Conclusion chapters. The body of the thesis will consist of the published papers.

   → **Partly achieved.** I have completed a draft of the introduction chapter and the subsequent chapters, including methods and the computational framework, mainly focusing on developing MESA-based stellar models.

Project 2: Explaining the skewness in the gamma-ray burst duration distribution using progenitor stars

Progressing with the previous work that includes analysis of density distributions, computations of free-fall timescales, and specific angular momentum budgets for extended MESA stellar grids. This provides a foundation to identify how the structure of stellar envelopes evolves and modifies accretion timescales and, consequently, the duration distribution of LGRBs. The aim is to connect late-stage stellar evolution to the canonical collapsar-driven long GRB scenario (Tarnopolski 2020; Perna, Lazzati & Cantiello 2018). This project investigates the role of progenitor stars in shaping the observed distribution of gamma-ray burst durations. The statistical distribution of those values is called the T_{90}-distribution. Where the T_{90}, denotes the time interval during which 90% of the burst fluence is observed. In the current phase of 2024/2025, the project has focused on writing a coherent astrophysical narrative in the form of a scientific research paper. In the paper, I wrote a strong introduction and contributed to the methods section, which connects the physics of LGRB progenitors, the structure of stellar envelopes, and the formation of the central engine to the statistical properties of the duration distribution of LGRBs.

The observed distribution of T_{90} values in LGRBs is known to be skewed rather than symmetric (Kouveliotou et al. 1993; Tarnopolski 2016, 2020). Previous studies have often attributed this skewness to a mix of progenitor channels or detector selection effects. Our work emphasises that the physics of stellar progenitors themselves can play a decisive role. In particular, the presence of extended stellar envelopes at the time of collapse alters the characteristic free-fall time, which in turn affects the accretion timescale of material falling into the central black hole, the duration of the central engine, and consequently, the observed duration of LGRBs (MacFadyen & Woosley 1999; Woosley & Heger 2006). We find that how the envelope structure of a star and free-fall physics are crucial to understanding the observed T_{90} distribution.

To carry out this project, MESA-based stellar evolution model grids from project I are used, covering a range of parameters such as masses from 10 to 100 M⊙, rotational velocities between 0.1 and 0.8 in Keplerian units, and metallicities from Z = 0.017 down to 0.00001 (Paxton et al. 2011; Paxton et al. 2013; Paxton et al. 2015; Paxton et al. 2018; Paxton et al. 2019). In addition to the work carried out in Project I, here I expanded my analysis to include the density profiles at the end of carbon core burning. These models served as input for the code developed by my collaborator, Dr. Hab. M. Tarnopolski, prof. UMK, which performs Monte Carlo-based statistical simulations to be compared with the observed T_{90} distributions. The resulting paper, intended for submission to Astronomy & Astrophysics, is currently in preparation. This section provides a detailed explanation of the physics used to set up the stellar models and their density profiles at the end of carbon core burning, as these directly determine the envelope's free-fall timescale (Woosley 1993; O'Connor & Ott 2011; Ertl et al. 2016).

Scientific goals:

1. **First scientific goal:** Understanding astrophysical link between stellar envelopes and skewed LGRB duration distribution.

   → **Successfully achieved.** Using density and free-fall timescale analysis from MESA models, the project explains how an increase in the size of the stellar envelope leads to an extended accretion timescale and thereby increase LGRB durations, providing a direct physical mechanism connecting progenitor structure to the asymmetry in T_{90} distributions of observed LGRBs (Tarnopolski 2020; Bromberg et al. 2012).

2. **Second scientific goal:** Draft a complete paper synthesizing previous technical analysis into a publishable scientific manuscript.

   → **Successfully achieved.** The methods section was completed, detailing the use of extended MESA grids across mass, metallicity, and rotation parameters. The analysis incorporated prior work on angular momentum transport and mass loss, confirming that compact progenitors emerge naturally under specific astrophysical conditions (e.g., low metallicity), and putting the framework in continuity with studies of LGRB duration distributions in the literature (Tarnopolski 2020; Bromberg et al. 2012).

3. **Third scientific goal:** Perform direct statistical comparisons between modeled free-fall timescales and observed T_{90} distributions catalogs.

   → **Ongoing.**

   → **This will be continued next year.** While the conceptual framework was established, detailed statistical testing against observational catalogs is still ongoing. This will be continued in the next academic year as part of the results and discussion sections of the paper, with explicit reference to BATSE (Koshut et al.

1996), Swift (Lien et al. 2016), and Fermi (Poolakkil et al. 2021) datasets.

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2. Information on courses passed within the Framework Program of Education (all classes must be included in your USOS account; those which are not cannot be included in this report) [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: Supervisor mentoring Final grade: ZAL Number of hours: 10 hours Number of ECTS points: 1 ECTS credit
3. Participation in scientific conferences** (confirmations required/ must be enclosed to the report) [name of conference, organizer, dates; form of participation; title of abstract, authors, etc.] 1. Conference title: European Astronomical Society Annual Meeting Date: 23 - 27 June 2025 Venue: University College Cork, Ireland 2. Workshop title: MESA School KU Leuven Date: 21 - 25 July 2025 Venue: The Arenberg science campus, KU Leuven, Leuven, Belgium.
4. Research trips or internships (confirmations required/ must be enclosed to the report) [Name of the institution, place, dates, description of the internship]. Not applicable
5. Submission of the doctoral dissertation – yes/no [delete as appropriate]. No

6. Teaching practice with students*** (confirmations required/ must be enclosed to the report)
[Title of courses, amount of hours]
Not applicable

7. Applying for a research grant. (confirmations required/ must be enclosed to the report)
[name of the grant, application's status, confirmation of submitting the application].
Not applicable

8. Sscientific publications. (confirmations required/ must be enclosed to the report)
Not applicable

9. Other achievements: (confirmations required/ must be enclosed to the report)

I together with my supervisor Dr. hab. Dorottya Szécsi, prof. UMK have recently started collaboration with *Mr. Ayush Garg*, a doctoral candidate under the supervision of *Dr. Amit Shukla (Associate professor)* at the Indian Institute of Technology, Indore (Madhya Pradesh, India). As part of this collaboration, Ayush plans to access and analyze my MESA stellar evolution models to support his own research objectives. Although this collaboration is still at a initial stage and no joint publication is currently planned. It is an additional international collaboration that I am actively pursuing.

10. Plans for further work on the doctoral dissertation.

Looking forward to academic year 2025/2026, the primary focus will be on finalizing the paper and thesis by going several rounds of correction and improving the paper and thesis draft and improving the paper and thesis draft, with special attention to drawing scientific conclusions from the comparisons to observations. If there is enough time I shall extend the analysis to binary progenitors and binary population synthesis frameworks. In this way, the project will continue to develop a comprehensive bridge between stellar modeling, population synthesis, and observational datasets of LGRB progenitors.

.........28-08-2025.................

Date

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.........28-08-2025............

Date

Dyrektor
Interdyscyplinarnej Szkoły Doktorskiej
"Academia Copernicana"

prof. dr hab. Iwona Łakomska

PhD student's signature	Supervisor's signature	Signature of the Head of ISD AC

Attachments:

1. Opinion of the supervisor(s)
2. Opinion of the doctoral student