NICOLAUS COPERNICUS UNIVERSITY IN TORUŃ

THE REALIZATION OF INDIVIDUAL RESEARCH PLAN

Name and surname	**Rafia Sarwar**
Project title	**Gamma-ray burst and gravitational-wave event rates: modern population synthesis**
Scientific disciplines	**Astronomy and Informatics**
Supervisor	**dr hab. Michal Hanasz and Dr. Dorottya Szecsi**

Year of study: I (academic year 2021 / 2022)

1. Report on the realization of individual research plan (IRP) The precise and documented information about the implementation of the tasks should be described according to the individual points of the individual research plan form:

a. Description of methodological assumptions and obtained research results/artistic achievements, including indication and justification of changes in planned research or artistic activities and methodological assumptions:

Description:

Over the last few years, observational and theoretical stellar astrophysics, compellingly, altered the paradigm of our existing knowledge of the evolution of massive stars. These massive stars are formed in the dense interstellar medium and evolve off to their final fate collapsing into compact objects. Stellar evolutionary models combined with binary population synthesis studies are often used to estimate statistical event rates of various associated phenomena such as core-collapse supernovae, gamma-ray bursts or gravitational-wave emission during the merger of compact objects. In spite of their significance, making predictions on these final phases based on evolutionary models of massive stars is a challenge in practice. The explosion physics of an exploding star is a complex problem governed by the stellar structure at the time of core collapse. For this reason, the development of a new algorithm is crucially required. For this reason, further investigations of how to associate the final fate predictions to evolutionary models is crucially required. For this end, my PhD project studies the astrophysical sources that are expected to be progenitors of gamma-ray bursts (GRBs). This can be achieved by developing a new computer routine 'FINFAT' to decide the final fate of stars given in a population expected to undergo based on the stellar models. These stellar models can be evolved using various stellar evolutionary simulations such as Modules for Experiments in Stellar Astrophysics (MESA) and Bonn Code.

b. Status of implementation of organizational undertakings and research/artistic tasks included in the project schedule

Scientific goals:

1. First scientific goal: To grasp good knowledge and training to use the MESA software, and critically interpreting the results of the MESA stellar evolution simulations in the context of GRB- and gravitational wave GW-progenitor theories. To achieve this, the special university lecture "Gravitational-wave progenitors" has been completed, and the most recent scientific literature was read and understood.

→ **Successfully achieved.** Basic training in the use of the MESA software was done. During this phase, MESA-expert Dr Poojan Agrawal (University of North Carolina, Chapel Hill, USA) and Dr Koushik Sen in the local massive star group were contacted as a scientific collaborators. A special lecture was done with an excellent mark. Scientific literature has been processed in the form of weekly "Journal Club" meetings with the supervisor and research group.

2. Second scientific goal: Preparation of simulation setups based on the existing literature and most recent observation used by I Horvath et al. (2020). Running preliminary models, deciding on the right temporal resolution ("profile" output frequency) and parameter output (which parameters should be computed and written out). This will serve as the basis of the development of the FINFAT code.
   → **Successfully achieved.** Preliminary models have been created and analysed. Basic diagrams have been plotted and interpreted. "Profile" output frequency is established, and parameter output (including the most important quantities such as the *specific angular momentum*) is decided upon.

3. Third scientific goal: Analysing the seminal results of Yoon et al. (2006), and planning the extension of these results in light of the most recent observational dataset [1, 3].
   → **Successfully achieved.** Yoon-data obtained, analyzed and discussed. Follow-up plan designed. New observational data GRBOX: Gamma-Ray Burst Online Index earlier used by Horvath et al. (2020), maintained and prepared for the purposes of the theoretical interpretation.

4. Fourth scientific goal: Preparation of a paper in which the results of Yoon et al. (2006) are revised and expanded upon, including the new observational comparison and the (single star) population synthesis.

   → **Partly achieved.** Preparing the publication is in progress. However, the first academic year could only be started with a very significant delay (in January instead of October, a full 4-months delay) due to Visa-related issues which were completely out of the hands of the Student. Therefore the last step – the single-star population synthesis – has been shifted for the second academic year.

References:

[1] I Horvath et al., *Monthly Notices of the Royal Astronomical Society*, Volume **498** (2) 2544–2553, 2020.
[2] S.-C. Yoon, N. Langer, C. Norman, *Astronomy & Astrophysics*, Volume **460** (1) 199-208, 2006.
[3] https://sites.astro.caltech.edu/grbox/grbox.php?starttime=700101&endtime=181231

c. Information on submitted research applications:

Not applicable.

d. Information on participation in scientific conferences, seminars or workshops, including the name, place and date as well as the nature of participation (organizer/participant) and the form of presentation of the results (poster, report, paper):

Conference name: The PHAROS Conference 2022

Date: 16 - 19 May 2022

La Sapienza University, Aula Magna, Piazzale Aldo Moro, 5, 00185 Rome, Italy.

Type of participation: Poster presentation

Title: Searching for binary black holes in the Milky Way with Laser Interferometer Space Antenna (LISA)

Conference name: XV Kopernikańskie Seminarium Doktoranckie

Date: 20 - 22 June 2022

Nicolaus Copernicus University, Toruń, Poland.

Type of participation: Invited talk

Title: "At the time of abstract submission it was named as Understanding early galaxies with the evolution of massive stars"

Later we changed the title: "From Stars to Galaxies"

Workshop title: Bringing Stellar Evolution and Feedback Together

Date: 25 - 29 April 2022

The Lorentz Center, Niels Bohrweg 2333 CA Leiden, Netherlands.

Type of participation: Coauthor in the paper written to summarize scientific goals and contributions of the workshop

Poster presentation including poster talk titled: Searching for binary black holes in the Milky Way with Laser Interferometer Space Antenna (LISA)

Workshop title: Best grant opportunity for new postdocs: how to successfully apply for Marie Skłodowska-Curie Postdoctoral Fellowship?

Date: 19 - 20 October 2022

Nicolaus Copernicus University, Toruń, Poland.

Note:

Certificates of participation are enclosed.

e. information on cooperation with domestic or foreign scientific institutions:

not applicable.

f. Apprenticeship:

Internship Project title: Searching for binary black holes in the Milky Way with LISA

Date: 21 September to 05 October 2022

Collaborator Names: Tassos Fragos, Simone S. Bavera

Collaborator's Institute: Departement d'Astronomie, Université de Genève, Chemin Pegasi 51, CH-1290 Versoix, Switzerland.

g. classes completed as part of the educational plan:

- Gravitational-wave progenitors
- Elements of occupational health and Safety and ergonomics (general training)
- Scientific data presentation and copyright I
- Scientific methodology
- Supervisory mentoring

h. other forms of the doctoral student's scientific activity connected with the education and implemented research project.

not applicable.

2. List of scientific papers (included in the list of scientific journals and peer-reviewed materials from international conferences of the Ministry of Higher Education and Science), which were written during the education at the Academia Copernicana Interdisciplinary Doctoral School:

During workshop at the Lorentz Center in Leiden, all attends compiled up a summary of their proposals in a form of a paper that has been accepted to the publications of the Astronomical Society of the Pacific titled as:

Bringing Stellar Evolution and Feedback Together: Summary of Proposals from the Lorentz Center Workshop

DOI: 10.1088/1538-3873/acb6b5

Publications of the Astronomical Society of the Pacific

TOPICAL REVIEW • OPEN ACCESS

Bringing Stellar Evolution and Feedback Together: Summary of Proposals from the Lorentz Center Workshop

Sam Geen[1,2,25,26], Poojan Agrawal[3], Paul A. Crowther[4], B. W. Keller[5,6], Alex de Koter[1,7], Zsolt Keszthelyi[1,8], Freeke van de Voort[9], Ahmad A. Ali[10], Frank Backs[1], Lars Bonne[11], Vittoria Brugaletta[12], Annelotte Derkink[1], Sylvia Ekström[13], Yvonne A. Fichtner[14], Luca Grassitelli[14], Ylva Götberg[15], Erin R. Higgins[16], Eva Laplace[17], Kong You Liow[10], Marta Lorenzo[18], Anna F. McLeod[19,20], Georges Meynet[13], Megan Newsome[21,22], G. André Oliva[19], Varsha Ramachandran[6], Martin P. Rey[23], Steven Rieder[13], Emilio Romano-Díaz[14], Gautham Sabhahit[16], Andreas A. C. Sander[24], Rafia Sarwar[25], Hanno Stinshoff[12,25], Mitchel Stoop[1], Dorottya Szécsi[25], Maxime Trebitsch[26], Jorick S. Vink[16], and Ethan Winch[13] – Hide full author list

Publications of the Astronomical Society of the Pacific, Volume 135, Number 1044
Citation Sam Geen *et al* 2023 *PASP* **135** 021001
DOI 10.1088/1538-3873/acb6b5

3. A list of research/artistic internships in external scientific centers, especially abroad, in which the doctoral student actively participated, i.e. conducted research or presented its results. The list should be accompanied by appropriate documentation and certificates.

In addition to my PhD project, I am currently working with Prof. Anastasios Fragkos (Gravitational Wave Science Center (GWSC), University of Geneva, Switzerland) on theoretical predictions for the future space-based gravitational wave observatory LISA, and gained valuable knowledge on this topic in the past two years. Prof. Anastasios Fragkos has longstanding experience and competence in the observational, computational, and theoretical aspects of theoretical astrophysics. During my internship visit of two weeks from 21 September to 05 October 2022, it was an exciting opportunity for me to work with the group at Geneva Observatory, University of Geneva.

Internship Project Description:

Most massive stars in the Universe (at least 8 times more massive than our Sun) are orbiting each other in the form of a binary stellar system. Predominantly, the fate of these stars, after the completion of their life cycle, is a remnant, known as a compact object. If these compact objects are insufficiently close orbits, they start losing orbital energy via gravitational wave (GW) emission, which leads to their inspiral. In 2015, the GWs from the inspiral of a binary black hole, a few seconds before the final merger, were detected, marking the dawn of a new field in astronomy, that of gravitational astronomy. In this project, I am looking into the future and the upcoming, first-ever, space-based GW observatory LISA. The project aims to explore the GWs emitted from compact-object binaries in our Milky Way galaxy, as they are expected to be observable with LISA. The study of the properties of these GWs will enable us to predict the astrophysical conditions of the formation of these binaries, and trace back earlier stages of their evolution. Some types of these binaries are expected to be so abundant that will be unresolved by LISA, forming some type of an “astrophysical noise” in the data.

Scientific goals:

1. First scientific goal: To construct a physically accurate model of LISA sources for the Milky Way using publicly available data from one of the most advanced galaxy formation simulations, the Latte simulation [1, 2] from the Feedback in relativistic environments (FIRE-2, [3]) project. This simulation provides spatially resolved information about the star-formation history and metallically evolution of Milky Way-type galaxies and their environments.

   → **Successfully achieved.** Using the Feedback in relativistic environments (FIRE-2) simulation I have associated each binary with down-sampled star particle from MW simulation and two-dimensional train kernel density estimator (KDE) based on the distance and age of star particles.

2. Second scientific goal: Combining this information with the population synthesis code POSYDON [4] which is being developed by the group of my proposed host advisor. The population is then evolved of these stars till the present age, accounting for gravitational wave energy loss [5], and then identifing those compact object binaries that could be potential sources for LISA.

   → **Successfully achieved.** As a first step, I familiarize myself with the POSYDON version 0.1 data. To evolve this synthetic population of stars using trained KDEs from FIRE-2 simulation till present age I created a dedicated code which evolve the population of BBHs from their formation to today computing properties such as chirp mass, effective spins,

inspiral and delay times.

3. Third scientific goal: Motivated by the growing sample of detected BBH merges by LIGO, I will investigate the detectability of the BBH population in both the LISA and the LIGO frequency bands [6], as a function of eccentricity and their horizon distances, using a Monte-Carlo approach [7, 8, 9].

   → **Partly achieved.** This code further computes the orbital properties (such as orbital separation, eccentricity and frequencies) of each BBH at the present time combined with signal-to-noise ratio using LISA sensitivity. These properties are then used to check the detectability of each BBH system. To preform test runs I was granted access to high-performance computing facilities, specifically the Yggdrasil high-performance computer cluster to run simulations for the project. While running these code simulations I came across some bugs in the code which resulted in inconsistent results. This project continued during year 2023 remotely debugging the code and resolving inconsistencies in it.

4. Fourth scientific goal: First draft of the paper.

   → **Initiated.** First draft of the paper is already written and is anticipated to complete during the third year.

References:

[1] Wetzel A. R et al., 2016, ApJ, **827**, L23.
[2] Hopkins P. F., 2015, MNRAS, **450**, 53.
[3] Sanderson et al., 2020, ApJ, **246**.
[4] Fragos *et al.,* 2023, *ApJS,* **264**, 45.
[5] Peters, P. C., 1964, Phys. Rev., **136**, B1224.
[6] A. Lamberts et al., 2018, MNRAS, **480**, 2704-2718.
[7] Sesana et al., 2020, MNRAS, **469**, 930-937.
[8] Breivik, Katelyn et al., 2020, ApJ, **898**.
[9] Nishizawa A., Berti E., Klein A., Sesana A., 2016, Phys. Rev. D, **94**, 064020.

4. A list of applications submitted by the doctoral student in competitions of the university or to external entities for funding of foreign travel or research/artistic activities. A copy of the sent applications and relevant decisions should be submitted as documentation.

The *University Center of Excellence for "Astrophysics and Astrochemistry"* fully funds this PhD position for four years including all the expenses for foreign business trips to participate in conferences, workshops and summer/winter schools. Workshop and conference to Lorentz Center and La Sapienza University were partially funded by the host institute and the University Center of Excellence. Whereas the internship during the academic year 2022 at the Geneva Observatory was supported by the collaborator Prof. Anastasios Fragkos's Swiss National Science Foundation (SNSF) Professorship grant P00P2_211006 (PI: Fragkos). Therefore, applying for an additional research grant is not necessarily required at this stage of doctoral studies.

5. A list of classes or workshops carried out outside the compulsory study plan that contributed to the development of the doctoral student's soft skills. The list should be accompanied by relevant documentation.

Listed in section (d and g)

6.Other scholarly or artistic/conservation achievements and activities not directly related to IRP.

not applicable.

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

1. Report on the realization of individual research plan (IRP) The precise and documented information about the implementation of the tasks should be described according to the individual points of the individual research plan form:
a. Description of methodological assumptions and obtained research results/artistic achievements, including indication and justification of changes in planned research or artistic activities and methodological assumptions:

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

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.

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

This research project represents a valuable collaboration with our colleague at Piwnice Astronomical Observatory, Mariusz Tarnopolski. This collaboration not only exemplifies our In this project, our joint focus is 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 possibilities like ultra-long gamma-ray bursts (ULGRBs) investigated by Perna et al. (2018). These varying timescales may result in the skewed distribution of duration T_{90} which is the time during which 90 percent of GRBs total energy is detected previously investigated by Tarnopolski (2020).

b. Status of implementation of organisational undertakings and research/artistic tasks included in the project schedule

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

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. These MESA models were created accessing the Hydra computer

cluster facilities in the Institute of Astronomy, Nicolas Copernicus University in Torun. The execution of these tasks on a high-performance cluster involved the power of 64 rapid-processing nodes.

MESA (single-star) models: 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 helps us to accurately represent and predict the key properties for the evolution and fate of massive stars.

For further analysis, 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. 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 from next 2024, 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.

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).

→ **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, are drawn from both observational data and theoretical models, has been done. This examination includes seminal works such as those by [2, 3, 4, 5, 6].

Additionally, various mass-metallicity relations, as outlined by [7, 8, 9, 10, 11, 12], 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 can 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 a code that integrates CSF models with our MESA models. 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 MESA single star models alongside the cosmic star-formation (CSF) are now being prepared for scientific publication. While the initial draft has been initiated, its completion requires additional time and the incorporation of further results.

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

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 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 seamlessly expanded using more recent MESA grids. To achieve that I have used MESA models from project I.

3. Third scientific goal: Separate and scrutinize models that evolve chemically homogeneously from the overall grid. Focus on detailed sanity 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 (BH) at its last stable orbit, relevant to the production of GRBs.

→ **Successfully achieved.** A key aspect of this project involved scrutinizing models that undergo chemically homogeneous evolution within the broader grid of stellar models. This in-depth analysis focused on certain 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 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 skewness of T90 distribution and LGRBs, particularly investigating if extended of the envelope of progenitor stars result in an varying accretion timescale that is associated with the skewness of T90 distribution for LGRBs.

→ This will be continued next year.

In summary, the research successfully accomplished several objectives, advancing our

understanding of stellar evolution, the properties of massive stars at critical phases, and their 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] Neijssel C. J., Vigna-Gómez A., Stevenson S. *et al.*, 2019, *MNRAS*, ***490***, 3740

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

c. Information on submitted research applications:

Not applicable.

d. Information on participation in scientific conferences, seminars or workshops, including the name, place and date as well as the nature of participation (organizer/participant) and the form of presentation of the results (poster, report, paper):

Conference name: 16th annual meeting of the VLT-FLAMES Tarantula Survey (VFTS) collaboration

Date: 27 - 29 March 2023
(Online participation)
Venue: MPA, Garching, Germany.
Type of participation: Poster presentation
Title: Progenitors of LGRBs: Are single stars enough?

Conference name: European Astronomical Society Annual Meeting

Date: 10 - 14 July 2023
Category of Symposium LS15: Magnetars as central engines across the Universe, EAS 2023
Venue: Kraków, Poland.
Type of participation: Poster and oral presentation
Title: Progenitors of LGRBs: Are single stars enough?

Conference name: Massive Triples, Binaries and Mergers 2023

Date: 17-21 July 2023
Type of participation: Online participation only
Venue: Leuven, Belgium.

Note:

Certificates of participation are enclosed.

e. information on cooperation with domestic or foreign scientific institutions:

not applicable.

f. Apprenticeship:

Due to travel restrictions, internships initially planned for the academic year 2023 have been postponed for upcoming years.

g. classes completed as part of the educational plan:

- History of Scientific Thinking and Inquiry
- Ethics and Intellectual Property
- Artificial Intelligence and the Future of Scientific Thinking
- Evolutionary biology
- Supervisory mentoring
- Scientific Data Presentation and copyright II
- Elements of Occupational Health and safety and Ergonomics

h. other forms of the doctoral student's scientific activity connected with the education and implemented research project.

not applicable.

2. List of scientific papers (included in the list of scientific journals and peer-reviewed materials from international conferences of the Ministry of Higher Education and Science), which were written during the education at the Academia Copernicana Interdisciplinary Doctoral School:

In preparation.

3. A list of research/artistic internships in external scientific centers, especially abroad, in which the doctoral student actively participated, i.e. conducted research or presented its

results. The list should be accompanied by appropriate documentation and certificates.

Due to travel restrictions, internships initially planned for the academic year 2023 have been postponed for upcoming years.

4. A list of applications submitted by the doctoral student in competitions of the university or to external entities for funding of foreign travel or research/artistic activities. A copy of the sent applications and relevant decisions should be submitted as documentation.

The *University Center of Excellence for "Astrophysics and Astrochemistry"* funds this PhD position for four years 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.

5. A list of classes or workshops carried out outside the compulsory study plan that contributed to the development of the doctoral student's soft skills. The list should be accompanied by relevant documentation.

not applicable.

6. Opinion of the supervisor(s) and other researchers on the progress of the doctoral student in preparing the dissertation.

Endorsement Letters are enclosed.

7. It is possible to submit additional opinions (maximum two) on the PhD student, prepared by scholars from other research centers, especially foreign, involved in the research conducted by the PhD student.

Endorsement Letter and Certificates of participation are enclosed.

8.Other scholarly or artistic/conservation achievements and activities not directly related to IRP. Completion of this point is optional.

not applicable.

The indicated materials should be submitted in digital version (pdf file), after approval of the supervisor(s), within 2 weeks before the interview date.

Date: ……24.11.2023……

Ph.D. student's signature

Scientific Supervisor's signature

Assistant Supervisor's signature

Lorentz center

Visiting Address:
Niels Bohrweg 1 & 2
2333 CA Leiden
The Netherlands

+ 31 71 527 5400
info@lorentzcenter.nl

Leiden, 9 September 2022

To whom it may concern

This is to certify that Rafia Sarwar (Interdisciplinary PhD School Academia Copernicana, Nicolaus Copernicus University) participated and presented a poster in the Lorentz Center workshop:

'Bringing Stellar Evolution and Feedback Together 2022'
from 25 -29 April 2022

On behalf of the organizers,

Daniëlle van Rijk

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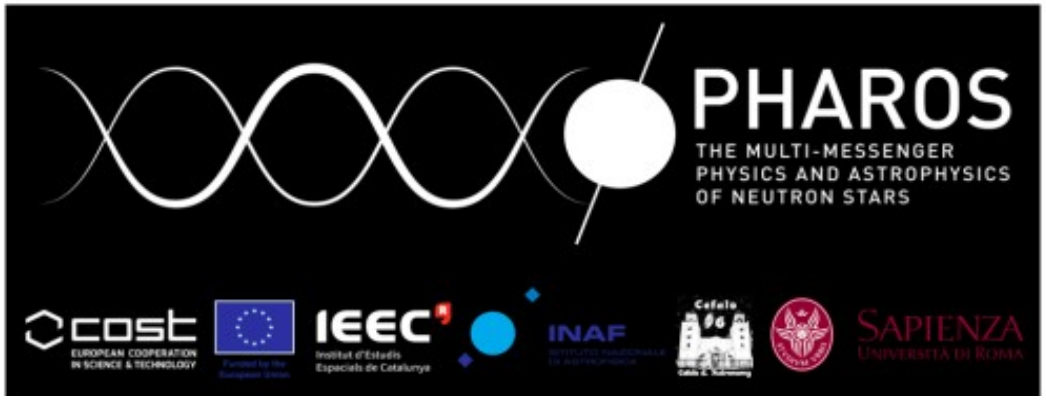


Certificate of Attendance

This is to certify that **Rafia Sarwar** take part in the International Astronomy Meeting "PHAROS 2022 Conference" (Rome, Italy, 16-19 May 2022).

Prof. Luciano Burderi
President "Cefalù & Astronomy"

Associazione Cefalù and Astronomy, c/o Fondazione Culturale Mandralisca,
via Mandralisca 13, I-90015 Cefalù (PA) - Tax Code 91010090826

UNIVERSITÉ DE GENÈVE
FACULTÉ DES SCIENCES
Département d'astronomie

Prof. Anastasios Fragkos (a.k.a. Tassos Fragos)
+41 22 379 24 81
Anastasios.Fragkos@unige.ch

Versoix, September 14th 2022

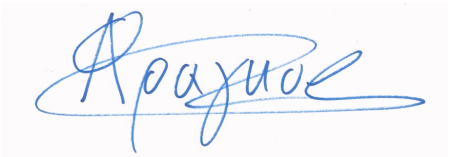
To whom it may concern

This is to certify that Ms Rafia Sarwar is invited to visit the Astronomy Department of Astronomy at the University of Geneva, from September 21st, 2022 to October 5th, 2022, in order to collaborate with myself and members of my group on the project "Modelling the population of binary black holes in the Milky Way detectable by LISA". Her travel and lodging expenses will be covered by the Swiss National Science Foundation Professorship grant P00P2_211006 (PI: Fragkos).

Please do not hesitate to contact me should you need any additional information.

With my best regards

Prof. Anastasios Fragkos



XV KSD

ZAŚWIADCZENIE

Zaświadcza się, że

Rafia Sarwar

zaprezentował(a) komunikat naukowy zatytułowany

UNDERSTANDING EARLY GALAXIES WITH THE EVOLUTION OF MASSIVE STARS

podczas XV Kopernikańskiego Seminarium Doktoranckiego.

Prof. dr hab. Edward Szłyk

Przewodniczący Komitetu
Organizacyjnego XV KSD

UNIWERSYTET
MIKOŁAJA KOPERNIKA
W TORUNIU

Toruń, 20 - 22 czerwca 2022

PPNT

Poznan Science
and Technology Park

CERTIFICATE

of participation in the workshop

for

Rafia Sarwar

Best grant opportunity for new postdocs:
how to successfully apply
for Marie Skłodowska-Curie Postdoctoral Fellowship
19.-20.10.2022 (12 teaching hours)

Paweł Kaczmarek
Coach

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PROGRAMME

NAWA

Max-Planck-Institut für Astrophysik
Max Planck Institute for Astrophysics

MPI für Astrophysik • Postfach 1317 • D-85741 Garching • Germany

MAX-PLANCK-INSTITUT
FÜR ASTROPHYSIK

Mrs Rafia Sarwar

Nicolaus Copernicus University, Poland

To whom it may concern

We hereby confirm that **Rafia Sarwar** participated online in the VFTS meeting which took place from 27-29 March 2023 in Garching, Germany.

Garching, March 27, 2023

The LOC

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FÜR ASTROPHYSIK
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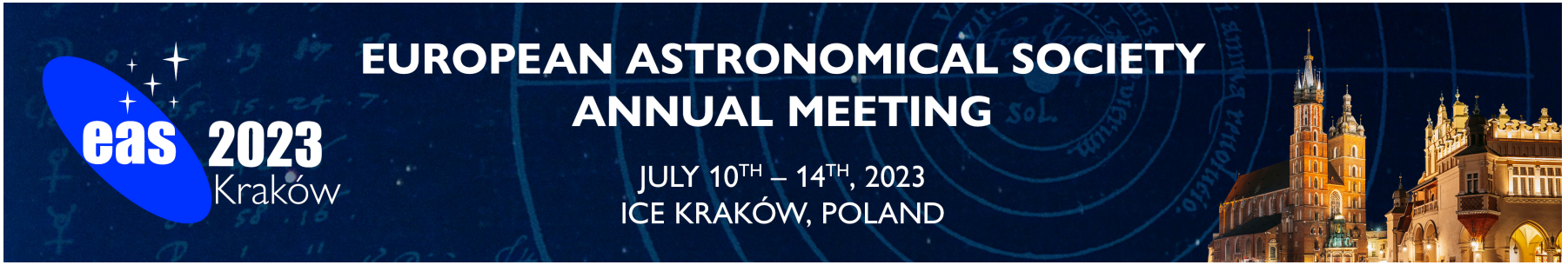
Postfach 13 17
85741 GARCHING B. MÜNCHEN



CERTIFICATE OF CONTRIBUTION

THIS IS TO CERTIFY THAT

Ms Rafia Sarwar

PRESENTED A/AN

ePoster

ENTITLED

Progenitors of LGRBs: Are single stars enough?

AT THE

EUROPEAN ASTRONOMICAL SOCIETY ANNUAL MEETING
HELD IN ICE KRAKOW CONFERENCE CENTRE, POLAND,
FROM JULY 10TH TO 14TH, 2023

Co-Chair of the Scientific Organising Committee
Agnieszka Pollo

Co-Chair of the Scientific Organising Committee
Stanisław Zoła

CERTIFICATE OF ATTENDANCE

THIS IS TO CERTIFY THAT

Ms Rafia Sarwar

ATTENDED THE

**EUROPEAN ASTRONOMICAL SOCIETY ANNUAL MEETING
HELD IN ICE KRAKOW CONFERENCE CENTRE, POLAND,
FROM JULY 10TH TO 14TH, 2023**

Chair of the Hosting Committee	Co-Chair of the Scientific Organising Committee	Co-Chair of the Scientific Organising Committee
Dorota Kozieł-Wierzbowska	**Agnieszka Pollo**	**Stanisław Zoła**

KU LEUVEN

Certificate of Online Attendance

for the conference

3,2,1: Massive Triples, Binaries and Mergers 2023

16-21 July 2023, Leuven, Belgium,

awarded to

Rafia Sarwar

Nicolaus Copernicus University

Torun

Poland

by the local organising committee