THE ANNUAL REPORT

Name and surname	Hanno Stinshoff
Project title	Expanding the BoOST massive star models to explain the formation of globular clusters
Scientific disciplines	Astronomy
Supervisor	Dr. hab. Dorottya Szécsi
Foreign scientific supervisor*	Not applicable
Assistant supervisor*	Not applicable

Year of study: .2nd. (academic year 2023/2024)

1. Description of the progress in the preparation of the doctoral dissertation and the progress in conducting scientific research
[Please, also refer to your Individual Research Plan]

Project 1: Expanding the BoOST model grids

This project is the continuation of the project of last year.
The original Bonn Optimized Stellar Tracks (BoOST) model grids from Szécsi et al. (2022) are stellar evolutionary models, created with the so-called Bonn Code to investigate the evolution of (single) massive stars. They range from 9 up to 500 solar masses, and occupy a broad range of metallicities, from that of the Milky Way (MW) down to a fraction (0.02) of the Small Magellanic Cloud (SMC). These models were converted into a format that a) filters out unnecessary data, therefore reducing the data load immensely, b) facilitates interpolation of the models to create a fine grid, and c) employs easy-to-use data tables to make application of the models easier.

The goal of this new project is to expand these grids by creating models that also vary in initial rotational velocity (from non-rotating (0 km/s) up to fast-rotating (500 km/s) models), increase the resolution (both time-wise, increasing the number of profiles per model, and the resolution of the initial parameters chosen, resulting in grids that show in a more resolved way at what parameter thresholds changes in the outputs happen) in interesting parts of the parameter space and bring them, just like their predecessor, into the BoOST format to enable easy application.

For that, first the models had to be created with the Bonn Code, which was partially achieved in Year I of the PhD. In Year II they were to be pushed further and converted into the BoOST format. Despite multiple technical difficulties I managed to progress in this goal by creating first boosted models and advancing the progress of others.

Scientific Goals:

1.) A big problem last year was that the code sometimes crashed without any foreseeable reason. This set back the computation drastically, since the loops in which the model computations were initiated were interrupted and had to be restarted.
To conquer that, the computations were continued in smaller loops, to lose less progress when they crash. On top of that the location of the computation was first moved from the connected external drive to the stationary machine itself, in case the connection to the external drive lead to the crashes. While this didn't lead to the desired result (Not only did the crashes still occur, but it also led to unnecessary bloating of the files that needed to be tidied up), it marked an important step in isolating the potential cause. The computation was slowly progressed, while the reason for the initial problem still needs more analysis in the future to be completely eliminated.

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→ Partly achieved.
The smaller loops make it manageable to work around the problem. It increased the manual workload, but this was not preventable.

2.) Handling the vast amounts of data started to become a problem, even without the bloated data from goal 1. I created 336 models in total, which in some cases each amount to multiple Gigabyte in size. This meant that the saving of backups and the storing of intermediate steps of the process required more space. After the first external hard drive previously used started to act up spontaneously, we bought a second one to ensure a secure deposit.
→ Successfully achieved.
The second hard drive was bought, formatted and added to the work station. It is used as additional back up storage and could also be used in the future as the main storage, if the problems of goal 1 persist.

3.) Bringing all the models to the End of core helium burning was a goal of the project. Last year already some models were brought to that point, but a lot of them still didn't reach it. This year the goal was to continue this process.
→ Partly achieved.
I managed to progress the models further than before, also employing a manual mass removal method called direct extension method (DEM) to possibly enable pushing models further that are too close to the so-called Eddington limit; stars with luminosity at this value are outputting radiation in such an intensity that the pressure is too high to be counterbalanced by gravity, therefore disrupting the star. For stars that are close to that limit the computation of their evolution can become increasingly difficult, resulting in the code crashing.
In some cases the DEM method could remedy the problem, but not in all of them (Agrawal et al., 2022). It remains yet to be seen, how I can solve the problem so that the rest of the models can be pushed till the end of core helium burning next year.

4.) Finally after pushing the models until the end of core helium burning they should be converted into the BoOST format. This includes the identification of Equivalent Evolutionary Points (EEPs) for all the models.
→ Partly achieved.
Just like in the original work in Szécsi et al. (2022) the EEPs are defined by certain criteria: 7 points in total are dividing the stellar tracks by identifying the beginning of the main sequence (A: 0% of the hydrogen in the core burned), a point during (B: "local minimum of the mass-loss rate corresponding to the bi-stability jump", or alternatively just 75% of the hydrogen in the core burned) and a point at the end of the main sequence (C: roughly 100% of the hydrogen in the core burned), then the beginning/bottom of the Red Supergiant Branch (D: Luminosity has a local minimum, or, in the case of blue loops without a base at the Red Supergiant Branch, the "middle of the loop blueward progression"), the middle of the helium burning phase (E: 50% of the helium in the core burned), a point close to the end of the helium burning phase (F: "Small dip in Luminosity" or roughly 90% of the helium in the core burned) and the end of the helium burning phase (G: 100% of the helium in the core burned).
For models that had actually reached the end of core helium burning, the process could be initiated, with some models successfully being transformed into the BoOST format (see goal 5). In some cases however, the EEPs were not chosen correctly yet, mostly due to the evolution diverging from the norm and therefore resulting in the criteria of the EEPs not being as straightforwardly applicable.
Out of the 336 models created, for around 110 the BoOST format was initiated. Still, quite a few of them had the suboptimal EEPs that still need correcting, only around 40 are in a state that seem representative of the actual evolution of the unboosted data.
It will continue to be a goal in the next year to modify these criteria for these new cases to enable the BoOST format for all models.

5.) For those models that both finished the evolution until the point of Core Helium exhaustion, the subset of models that also showed the correct choice of EEPs (see goal 4) was ready to be converted into the BoOST format. This meant that the EEPs were used to filter unnecessary data in-between these points and converting the output into easy-to-read data tables.
For the filtering the data is reduced to 608 data lines per model, with the EEPs' lines corresponding to lines 1, 151, 252, 403, 429, 505 and 608 (from A to G, cf. Szécsi et al., 2022)
→ Partly achieved.
The subset of models with successful identification of all EEPs showed that there are multiple models properly

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displaying the evolution of the model in the BoOST format. However, at the moment there are not enough models at this point to do continue with the interpolation (see goal 6), so pushing the models further (see also goals 3 and 4) is a necessary step still needed to be completed in Year III.

6.) Finally after converting the models into the BoOST format, they can be used for interpolating to create dense grids. With this the changes in the output with respect to the input parameters can be described with a much better resolution.
→ Not achieved.
At the moment not enough models have reached the BoOST format to enable a proper interpolation. This remains a goal for next year.

Once the models are fully ready, I plan to use them with WINDCALC (see project 2) to investigate globular cluster abundance anomalies (cf. for example Bastian & Lardo, 2018) in Year III and IV. While the modeling is still in progress, I already started to learn the details of WINDCALC in the collaboration with Richard Wünsch:

Project 2: Investigating the winds of stellar populations with varying wind descriptions:

As part of my collaboration with Richard Wünsch (Astronomical Institute of the Czech Academy of Sciences, Boční II 1401/1, 140 00 Prague, Czech Republic) I visited Prague and further established my presence as a researcher.
This internship aimed to provide insight into the WINDCALC code (cf. Wünsch et al., 2017) that will be used later on in my PhD to analyze the cluster winds of synthetic populations based on my own models (from Project 1, as a goal for Year III), similar to the work of Szécsi & Wünsch (2019), as well as create a separate project for publication by improving on the WINDCALC code myself and doing a parameter study to investigate optimal settings for a scenario like the one I will apply in the future.

Scientific Goals:

1.) I was already familiar with the original BoOST model grids, but I needed to understand how they are integrated into the WINDCALC code. I got the raw Bonn Code models and needed to convert them into the BoOST format. For that I needed to identify EEPs (see Project 1) of the models that are required to perform the conversion process.
→ Successfully achieved.
As the models used in this project are the same as in Szécsi et al. (2022), the choice of EEPs with their criteria is easier than in project 1. This means that there were no models where the EEPs weren't identified correctly. The BoOST format conversion happened without any issues.

2.) After identifying the EEPs the models are converted into the BoOST format. This includes the filtering of data between EEPs to reduce the data load, the interpolation of the models into fine grids and creating easy-to-use data tables.
→ Successfully achieved.
Identifying the EEPs facilitated the application of the BoOST format, creating data tables with 608 lines for each model, with a fine resolution over the whole parameter space.

3.) One of the main goals was to learn more about the WINDCALC code. I not only got a much deeper understanding of how the code works, but was also able to help improve it by adding multiple wind velocity recipes to it to facilitate a more flexible handling of the data, depending on the requirements of the user.
→ Successfully achieved.
I updated the WINDCALC code with new wind velocity formulas and verified the validity of their results. This included an extensive literature study on the topic and an implementation of 4 entirely new wind formulas for different spectral types (cf. Lamers et al., 1995; Krtička et al., 2021; Sander and Vink, 2022; Howarth and Prinja, 1989; and Prinja et al., 1990) and a rewrite of the old code to facilitate the easy choice of these (and also old) formulas depending on the need.
It also included the addition of a module allowing the free choice of metallicity scaling for separate spectral types, the updating of the parser of the code to improve the help section of the code, and the use of the git structure of the project to create a new main version of the code, integrating my changes in a proper way.

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4.) I am currently using this new and improved code to investigate optimal parameters (like the choice of Wolf-Rayet (WR) star wind prescriptions or which initial mass function (IMF) to chose, cf. for example Kroupa, 2001) to apply in population synthesis, so that I can use them for the population (based on my own models) in the future, and this investigation is publishable and currently prepared for submission to a journal.
→ Successfully achieved.
The internship resulted in the creation of populations based on the original BoOST models, utilizing varying wind velocity formulas for comparison. This produced many plots and figures usable for publication.

5.) The results of the project need to be formulated and organized in a complete paper draft that can then be submitted to a respectable journal.
→ Initiated.
Although publishable results were already created, the organization and formulation is still in initiation.
The results still need to be properly analyzed to draw conclusion for the future. Some have already been established, but the presentation of them needs to be improved, while others are still in examination.
On top of that it needs to be seen whether more results can be drawn out of the data. This is still an ongoing process.
Finally, choosing the right words and bringing everything in a context that is needed for a professional outline remains a goal for the third year.

References (in order of appearance):

[1] D. Szécsi, P. Agrawal, R. Wünsch and N. Langer, “Bonn Optimized Stellar Tracks (BoOST) - Simulated populations of massive and very massive stars for astrophysical applications”, *Astronomy & Astrophysics*, vol. 658, 2022, doi:10.1051/0004-6361/202141536

[2] P. Agrawal, D. Szécsi, S. Stevenson, J. J. Eldridge, and J. Hurley, “Explaining the differences in massive star models from various simulations”, *Monthly Notices of the Royal Astronomical Society*, vol. 512, no. 4, OUP, pp. 5717-5725, 2022. doi:10.1093/mnras/stac930.

[3] N. Bastian, and C. Lardo, “Multiple Stellar Populations in Globular Clusters”, *Annual Review of Astronomy and Astrophysics*, vol. 56, pp. 83-136, 2018. doi:10.1146/annurev-astro-081817-051839

[4] R. Wünsch, J. Palouš, G. Tenorio-Tagle, and S. Ehlerová, “The formation of secondary stellar generations in massive young star clusters from rapidly cooling shocked stellar winds”, *The Astrophysical Journal*, vol. 835, no. 1, 2017, doi:10.3847/1538-4357/835/1/60

[5] D. Szécsi and R. Wünsch, “Role of Supergiants in the Formation of Globular Clusters”, *The Astrophysical Journal*, vol. 871, January 2019, p. 20, doi:10.3847/1538-4357/aaf4be

[6] H. J. G. L. M. Lamers, T. P. Snow and D. M. Lindholm, “Terminal Velocities and the Bistability of Stellar Winds”, *The Astrophysical Journal*, vol. 455, IOP, p. 269, 1995. doi:10.1086/176575.

[7] J. Krtička, J. Kubát, and I. Krtičková, “New mass-loss rates of B supergiants from global wind models”, *Astronomy & Astrophysics*, vol. 647, March 2021, doi:10.1051/0004-6361/202039900

[8] A. A. C. Sander and J. S. Vink, “On the nature of massive helium star winds and Wolf-Rayet-type mass-loss”, *Monthly Notices of the Royal Astronomical Society*, Volume 499, Issue 1, November 2020, Pages 873-892, https://doi.org/10.1093/mnras/staa2712

[9] I. D. Howarth and R. K. Prinja, “The Stellar Winds of 203 Galactic O Stars: A Quantitative Ultraviolet Survey”, *The Astrophysical Journal Supplement Series*, vol. 69, IOP, p. 527, 1989. doi:10.1086/191321.

[10] R. K. Prinja, M. J. Barlow, and I. D. Howarth, “Terminal Velocities for a Large Sample of O Stars, B Supergiants, and Wolf-Rayet Stars”, *The Astrophysical Journal*, vol. 361, IOP, p. 607, 1990. doi:10.1086/169224

[11] P. Kroupa, "On the variation of the initial mass function", *Monthly Notices of the Royal Astronomical Society*, vol. 322, pp. 231-246, 2001, doi:10.1046/j.1365-8711.2001.04022.x

2. Participation in classes (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].

Name of the course: Applied Data Analysis and Statistics
Course code on USOS: 7405-AC-ADAS-1
Form of classes: Discussion Seminar
Final grade: 5
Number of hours: 50 hours
Number of ECTS points: 2 ECTS credits

Name of the course: Scientific Data Presentation and Copyright I
Course code on USOS: 7405-AC-SDPC1-1
Form of classes: Discussion Seminar
Final grade: 5
Number of hours: 10 hours
Number of ECTS points: 1 ECTS credits

Name of the course: Successful Grant Application
Course code on USOS: 7405-AC-SGA-1
Form of classes: Discussion Seminar
Final grade: 4.5
Number of hours: 10 hours
Number of ECTS points: 1 ECTS credits

Name of the course: Supervisory Mentoring
Course code on USOS: 7405-AC-SMEN-1
Form of classes: Supervisory Mentoring
Final grade: 5
Number of hours: -
Number of ECTS points: 4 ECTS credits

Name of the course: Scientific Methodology
Course code on USOS: 7405-AC-SM-1
Form of classes: Discussion Seminar
Final grade: 5
Number of hours: 30 hours
Number of ECTS points: 3 ECTS credits

Name of the course: Gravitational Waves Progenitors
Course code on USOS: 7404-WA-PFG
Form of classes: Course
Final grade: 5
Number of hours: 30 hours
Number of ECTS points: 3 ECTS credits

Name of the course: Occupational Safety, Health and Ergonomics
Course code on USOS: 9001-BHP-5-SD

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Form of classes: Tutorial Final grade: ZAL Number of hours: 5 hours
3. Participation in scientific conferences** (confirmations required) [name of conference, organizer, dates; form of participation; title of abstract, authors, etc.] Conference name: EAS annual meeting 2024 (certification handed in at UMK, but not accounted for in USOS yet) Date: 01 - 05 July 2024 Type of participation: Poster presentation (Title: Abundance Anomalies in Globular Clusters and their Possible Origin in Multiple Generations Including Massive Stars) Link to Poster: https://k-poster.kuoni-congress.info/eas-2024/gallery#/poster/3554b366-c514-495e-a8d8-8cb39b8dbe5d Venue: Padova Congress – Centro Congressi – Fiera di Padova, Via N. Tommaseo 59, 35131 Padova, Italy
4. Internships (confirmations required) [Name of the institution, place, dates, description of the internship]. Name of the internship: „Learning the application of WINDCALC code and investigating the winds of populations with various initial parameters" Institution, Place: Astronomický ústav AV ČR, Boční II 1401, 141 00 Praha 4, Czech Republic Date: 15.4. - 15.5.2024 Number of hours: 160 hours (1 month) Description: I analyzed synthetic populations based on stellar evolutionary models created with the so-called Bonn Code by using the WINDCALC code created by Richard Wünsch, who was my supervisor during this internship. For more details refer to Project 2 in the description.
5. Initiating a doctoral assessment process [Shortly describe the status of the assessment process] Not applicable
6. Submission of the doctoral dissertation – no [delete as appropriate]. Not applicable
7. Teaching practice with students*** [Title of courses, amount of hours] Name of the course: Gravitational Waves Progenitors Course code on USOS: 7404-WA-PFG Form of classes: Course Number of hours: 2 hours Link to presentation: https://wwwold.astro.umk.pl/~hanno/Hanno/presentations/Lectures/001_GWprog-Class5_HannoStinshoff.odp

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Note: As I had already attended the lecture two years prior without being able to do the exam due to not being enlisted in UMK yet, and because the topic of the lecture was exactly what I am working on in my PhD, I not only attended the biggest part of the lecture as a student (cf. The section "2. Participation in classes"), but I also took part as a teaching assistant (TA) by holding a two-hour lecture for the other students on a subject that I am especially familiar with, and by attending some exams of other students, including asking exam questions I needed to come up with on my own.
8. Applying for a research grant. [name of the grant, application's status, confirmation of submitting the application]. The research of the student in question is covered by the National Science Center (NCN), Poland under grant No. OPUS 2021/41/B/ST9/00757. There is no need for the application for a research grant anymore.

……05.09.2024…………………….
Date

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

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