**Evaluation report by the opponent about the academic dissertation (ID: dc_1914_21) entitled „Origin of the chemical elements heavier than iron and of meteoritic stardust from asymptotic giant branch stars" submitted in 2021 by the candidate Dr. Maria Lugaro PhD for the title and degree of Doctor of Science of the Hungarian Academy of Sciences (DSc of the HAS)**

## Scientific objectives, actuality of the research

There is a long lasting debate to explain the origin of elements heavier than the iron in the Solar System. The old paradigm is that the supernovae produced these elements and contaminated the presolar nebula. This paradigm is challenged when the nuclear astrophysicists claimed that the AGB (Asymptotic Giant Branch) stars can produce elements heavier than iron and the presolar nebula were contaminated by the products of nucleosynthesiis processes in AGB stars.

The motivations, open questions and related science objectives, aims of research are summarized in the following points:

1) Since many aspects of production of heavier elements than iron and the nucleosynthesis in AGB in general are not understood hence the refinement of old models even modifications them generating new models can improve the quantification of the products of nucleosynthesis, efficiency of the mass loss, which controls the lifetime of these stars. Computer models of mixing, diffusion processes, fine points of s- and r-porcesses, neutron capture process are worth to apply and renew for AGB stars. Even, the neutron capture cross sections play a crucial role obtaining s-process results.

2) Another major fundamental question is that of the existence of the i-process (intermediate neutron capture process) and its possible occurrence in nature. The i-process is probably driven by proton ingestion into a He-burning region, which allows production of the neutron source $^{13}C$ via proton captures on $^{12}C$ and the release of neutrons over a very short time scale. The less explored i-process could be important in AGB stars. Consequently, to study the i-process and apply that to the AGB stars may lead to new results in this unexplored field.

3) Meteoritic stardust grains from AGB stars provide extremely powerful high-precision constraints on AGB nucleosynthesis (Section 2.4.2). Meteorite grains carry anomalies in major and trace elements, including many refractory elements heavier than iron. We know that the vast majority of this stardust originated in AGB stars, where dust formation is observed, however, the grains do not carry direct information on the mass and metallicity of their parent stars (as it is possible to derive instead from spectroscopic observations). Therefore, we need to accurately and precisely identify the mass and metallicity of their AGB parent stars.

4) Another question to be addressed by AGB nucleosynthesis is the long-standing problem of the origin of short-lived radioactive nuclei in the early Solar System. Furthermore, in the Galaxy the AGB stars are the main source of short-lived

radioactive nuclei produced by the s-process and their role still needs to be fully exploited to better understand the events in the prehistory of the matter in the Solar System.

**These research aims are challenging and very timing to resolve the problem of pruduction of elements heviear than iron by AGB stars.**

## Methodology and feasibilty of the research – expertise background

The vast majority of the work presented in the dissertation is based on the comparison between theoretical, computational model predictions of the evolution and nucleosynthesis of AGB stars and a variety of observational constraints. In the dissertation the computational tools, nuclear reaction networks, and input physics, including the nuclear reaction rates, used to calculate the theoretical predictions are described in detail. The background related to the different observational constraints, some of which derive from spectroscopy of different types of stars, and others from the laboratory analysis of meteorites are described. Observational evidence from these various types of objects is obtained using completely different methodologies. Therefore, comparing these to the model predictions requires different approaches for the differing observational constraints. One of the main strengths of the work is the ability to exploit these many different sources of information.

Applied methods were the stellar structure models, the dppns45 code handling the mixing, nuclear networks, nuclear reactions, the inclusion of the $^{13}C$ pockets, observational constraints as the results from stellar spectroscopy, laboratory results of analysing stardust grains, results of short-lived radioactive nuclei in early Solar System.

The candidate started her research in early 2000s during the preparation of her PhD thesis in the research team conducted by professor  and her PhD thesis supervisor John Lattanzio of the Monash University, Australia applying three different stellar evolution models. She used the Torino post-processing code exploring the s-process and made predictions the products of s-process. She defended his PhD Thesis enditiled „Nucleosyntheis in AGB stars" in 2001.  From October to December 2001 she was visiting post-doctoral associate at the University of Notre Dame, USA. During her post-doctoral works she developed a nuclear network using the Monash dppns45 code. Until February 2005 she was post-doctoral associate at University of Cambdridge, UK, From October 2005 to September 2008 she worked as research fellow at University of Utrecht the Netherlands. From November 2011 to April 2014 she was research fellow, senior lecturer and adjunct  senior research fellow at Monash University, Australia.

In the meantime from the beneficious collaboration between Torino Group and Gerry Wassenburg of Caltech the elements produced by the s-process were explored in context of the meteoritic stardust of teh early Solar System. A by-product of this work was that the canddidate explained the contradiction between the half-lifeimes and abundances of 182Hf and 129I which was described in the Theses 4(a) of this dissertation.

In Hungary between 2014 and 2017 the candidate carried out in her study of AGB stars and the application of the results in study of meteorites as project leader in the frame of the program „Lendület" („Momentum") of the Hungarian Academy of Sciences.

## Significance of the ERC RADIOSTAR project in the research

There is a key project lead by the candidate, which is important in the dissertation and resulted new results in the exploration of the origin of the radioactive elements in the Solar System: this was the ERC RADIOSTAR1 project which is a significant grant in order to support the research and the candidate played deterministic role as project leader of that porject. The ERC RADIOSTAR1 (Radioactivites from stars to the Solar Systems) project running from September 2017 to August 2022 is based on the work presented in the chapter of „Short-lived radioactive nuclei and the origin of the Solar System Matter" as pilot studies. RADIOSTAR is a project of the Consolidator Grant (CG) scheme of the European Research Council (ERC) ERC-2016-COG - Grant Agreement 724560.

## Evaluation of the publication activity

The candidate´s first scientific publication was appeared in the journal Memorie della Societá Astronomia Italiana in 1996. before 2001, the defense of her PhD theses altoghether 38 publications presented her scientific results. Before 2021, the completing of her academic dissertation alltogether 262 publications were appeared and among these in 46 publications the candidate is the first author. In summary, after her PhD thesis until her academic dissertation 224 publications were appeared, which means that she were actived and pruductive in the science after reaching her PhD degree. After submission of her academic dissertation before September of 2022 – i. e., the evaluation of this dissertation – she published 17 publications in which she is the frist author in 6 publications, which means she continues her research activity. There are two maxima in the distribution of her publications: one is between 2012-13 and the second is between 2016-2021 which is connected to the ERC project. Value of the Hirsch-index (H-index) is 38 from the interval of 1996 and September of 2022 (practically before 2021 the year of competing of her academic dissertation).

**According the the aforementioned works and reseearch results it is obvious that candidate´s international level embedding of the respected works and results the feasibility of her research plan can eaily be completed.**

## Structure, content, and clarity of the dissertation

The arced dissertation to be assessed consists of 150 sheets with 142 numbered pages. The dissertation consists of six chapters. The chapters from 2nd to 5th present the motivation, science questions, methodology and new results are well organized in thes chapters consequently as follows: the motivation, methodology, new results, discussion – including the comparisons with earlier works and results, summary and conclusions are presented. At the beginning these chapters all the related publications of the candidate are given just below the title of the chapter or sections within that. Its consequence is that the reader may consult with these publications for the further details. The six chaptes are briefly in a nutshell the following:

***Introduction*** presents a retrospective view of the history of the observational background of chemical elements in the Universe, nucleosyntheis processes in stars, neutron-capture elements, general properties of neutron-capture processes, and in this context description of neutron captures in AGB stars. In the Introduction the open questions on the discipline and motivation of the recent research, namely, the main objectives and overview of the thesis are also presented.

***Second chapter*** is the Methodology, which descibes the applied methods, i. e., the theoretical background of applied models of stellar evolution and nucleosyntheis, stellar structure models, computer codes, and highlights the *dppns45* code which elaborates the mixing, nuclear networks, nuclear reactions, and the crucial problem of the inclusion of the $^{13}C$ pocket. methodology chapter also describes the constraints of observations and laboratory measurements as the aspects of stellar spectroscopy, stardust grains, and short-lived radioactive nuclei in the early Solar System since the dissertation work focused to the early interval of the Solar System which is related to the short-lived radioactive nuclei.

***Third chapter*** presents new result about the neutron captures in AGB stars of low metallicity. Moreover, new results about the neutron captures in post-AGB stars in the Large Magellanic Cloud (LMC) and Small Magellanic Cloud (SMC) are also presented.

***Fourth chapter*** clarifies the origin of meteoritic stardust from AGB stars alongside the discussion pof neutron-capture elements in mainstream SiC grains, explanation of the origin of micron-sized SiC grains from AGB stars of super-solar metallicity, discussion of Si in stardust SiC, and presenting of results about Group II oxide and silicate stardust. Since the Fourth chapter completes the research of the origin and prooperties of stardust particles a section of Implications and outlook summarizes the aforementioned results and their consequences on the meteoritic dust and related laboratory works.

***In the Fifth chapter*** the role of short-lived radioactive nuclei in the origin of Solar System matter is discussed with presentation of imporant new results.

The dissertation contains ***two Appendices,*** which are very useful and the these could be enlighten the readers as to the specific expressions of the discipline: Appendix A is the list of the main acronyms and abbreviations, and Appendix B is the list of nuclear species in the *dppns45* network.

After checking the format of the dissertation, i. e., the linguistic quality and the adequate language expressions, and scientific presentation standards of the dissertation matches to the usual academic standard requirements of a dissertation. The sentences and statements in both the dissertation and theses are clear and understandable. Extensions of the parts of the dissertation (text parts, chapters, sections, number of figures and tables) are suitable. **Hence, according to its format the dissertation is suitable and appropriate for official evaluation and defense procedure.**

## Minor issues: corrections, typo errors

Word „stardust" is applied in the dissertation as subjects of analysis of elemental composition of the dust particles originated from stars, which are in star forming regions and in presolar nebula. But there is another meaning of the word „stardust" in the astronomy, space research, and cosmochemistry: it is the NASA's Stardust space mission, the name of the spacecraft (spaceprobe) which collected dust particles in the interplanetary space and cometary dust particles during the flyby at comet 81P/Wild 2 in 2004. In order to clarify the difference between the meaning of th specific dust particles and the name of a spacecraft at the first occurrence of the word „stardust" in the dissertation mainly for the future readers, beginners, students who read the informative dissertation otherwise. Of course many readers are experts or know the meanings of this word. Moreover, the „stardust grains" (e.g., page „V" and Chapter 6) in the text throughout the dissertation are not identical with the grains collected by the Stardust mission but grains related with terrestrial meteoritic samples.

On page 105 the abbreviation „Gr" is a typo error. The abbreviation „Gyr" (gigayear) would be the correct instead.

These minor points have not influence for the scientific results of the dissertation.

## Theses of the dissertation

Results of the submitted dissertation are summarized in four thesis points, which are based on 12 refereed papers published by the author and her co-authors in highly respected science journals in the fields of astronomy and astrophysics, geochemistry and cosmochemistry: A&A (2), ApJ (5), ApJL (1), Geochim. Cosmochimica Acta (1), Nature Astronomy (1), Science (2).

The first thesis point is related with 2 publications: A&A (1), ApJ (1). In both papers the candidate is the first author.

The second thesis point is related with 6 publications: ApJ (34, ApJL (1), Geochemica, Cosmochimica Acta (1). In 5 publications the candidate is the forst author, in 1 publication (Geochim. Cosmochim, Acta) the candidate is the second author. In the paper where the candidate is the second author the contribution to the paper of the first two authors was equivalent.

The third thesis point is based on 3 publications: AcA (1), Nature and Astronomy (1). In both publications the candidate is the first author.

The fourth thesis point is related with 2 publications appeared in the journal Science, in both of them the candidate is the first author.

**The 1st thesis point** proves that either the slow neutron-capture (s) process or combination of rapid neutron-capture (r) process cannot explain the observed abundance in metal poor halo stars and post-AGB stars. The research presented in the dissertation (Chapter 3) proved that the intermediate neutron-capture (i) process is operational in these stars.

I found that the revealed role of the i-process to explain the observed abundance in metal poor stars and post-AGB stars is a new result of this research.

**The 2nd thesis point** addresses the solution that the stardust silicon carbide (SiC) grains that carry the signature of the s process formed in C-rich AGB stars of initial masses between roughly 2 and 4 solar masses and metallicity from solar up to roughly twice solar. The grain sizes increase, roughly from smaller to larger than a micrometer, with increasing the metallicity of the AGB parent star (Chapter 4).

The significance of this thesis point is that its results establish connection between stardust silicon carbide (SiC) grains and the C-rich AGB stars as sources and properties of these grains.

**The 3rd thesis point** reveals that the stardust oxide and silicate grains showing strong depletion in $^{18}O$, known as Group II grains, originated from AGB stars with initial masses above roughly 4 solar masses where proton captures occur at the base of the convective envelope (see e.g., Section 4.4).

This thesis point gives solution the $^{18}O$-depleted silicate grains and suggests their origin from AGB stars with 4 solar masses.

**The 4th thesis point** finds that the origin of the abundances of radioactive nuclei made by the r- and s-processes in the early Solar System is decoupled, and provides us with independent clocks for the last r-process (a neutron star merger or a rare supernova) and s-process (an AGB star) source that contributed matter to the Solar System. The abundances of the heavy radioactive nuclei of p-process origin should be produced by both Type Ia and core-collapse supernovae (Chapter 5).

This thesis provides brand new approaches and results about the origin of the early solar nebula from which the Solar System formed. In addition, the role of neutron star mergers as new source of the elements heavier than the iron is highlighted.

**I consider that the theses of the dissertation contain unprecedented new results and the thesis points are based on the candidate´s own work. In summary, I accept all the theses as new scientific results in the discipline**

## Opponent´s questions to the candidate with respect to the science presented in the dissertation are the following:

1) This question addresses the problem of the formation of gold (Au) in the Universe. To create elements heavier than iron - such as gold, (Au) silver (Ag), thorium (Th) and uranium (U) - the rapid neutron-capture process, or r-process, is required. This can take place in really energetic explosions, which generate series of nuclear reactions in which atomic nuclei collide with neutrons to synthesise elements heavier than iron. We know now that the kilonova explosion generated by a neutron star collision (binary neutron star merger) is an energetic-enough environment for the r-process to take place (see page „V" of the dissertation), which is obvious and widely accepted.. However, on page 63 of the dissertation the candidate quotes the

work by Chiaki Kobayashi, Amanda Karakas and Maria Lugaro (the candidate herself as co-author) (2020, ApJ, 900, id. 179). In this work they constructed Galactic Evolution (GCE) models for all stable elements from carbon (C) (A=12) to uranium (U) (A=238) in which these models allow to discover consistencies, and inconsistencies, that arise only by considering all of the elements together. For example, the authors found that silver is overproduced by a factor of six, while gold is underproduced a factor of five in the model (see Figure 32 of Kobayashi et al,, 2020). But it was first believed the sufficient amount of the gold production in the Galaxy after revealing of gold just after the kilonova explosion observation in 2017. **Question:** What do you suggest to resolve the problem of underproduction of the gold?

2) On pages 46 and 107 of the dissertation the candidate highlights only the role of AGB stars locate in stellar association (OB association) in which or in its proximity the Sun and Solar System formed, presumably, and those sibling AGB stars in the stellar association contamine their environment with elements hevier than the iron. However, there are other model scenarios of Sun forming regions, which consider the birthplace of the Sun and Solar System: these are open clusters, which can contain AGB stars. According to the claimed types and abundences of elements considered in the dissertation only the a stellar association is the birthplace of the Sun and Solar System unambigously. **Question:** Why only the stellar association was considered and highlighted in the dissertation and the open cluster has not been discussed as possible place of formation of the Sun?

3) This question is connected to using of the results of the research and the future works. In the near future the lunar exploration by landers, rovers and humen expeditions will speed up again. Former manned lunar landing missions and automatic returning lunar probes collected both surface and penetrator lunar soil samples in which the nearby and relatively young supernova traces were found. There are three sub-questions as follows. **Question a):** Is there any opportunity that traces of early solar system contaminating presolar AGB stars produuced elements heavier than iron will be revealed in either the old and future lunar samples? **Question b):** Similarly, is there any chance to find traces of presolar AGB stars in terrestrial samples in the oldest geological samples (rocks, soils, sediments, terrestrial or lunar meteoritc samples, lunar regoliths)? **Question c):** In the future explorations which processes and methods do you prefer and propose to apply in the most accurate and reliable radiometric age determination (dating using radioactive decay) of very old meteoritic or other soil samples originated from the ancient epochs of the Solar System and how long time intervals are covered by those dating methods?

## Summary of the quintessential results of the dissertation (in English)

New models and model refinemetns have been elaborated and applied successfully to improve our understanding the details and role of various nucleuosynthesis processes in AGB (Asymptotic Giant Branch) stars, Important new result is claimed that the nucleuar i-process (intermediate neutron capture process) has important rolte in the nucleosynzhesis of AGB stars, which is a brand new result. Modeling has shown the also important role of

AGB stars in the contamination of interstellar matter and presolar nebula (from which the Sun and Solar System formed) by elements heavier than iron, which overrides. This is a new paradigm comparing the the earlier models which favoured the production of heavier elements by supernovae exclusively. Important new approach and results of the researh is the identification of the elements heavier than iron of AGB stars origin in stardust (meteoritic material).

In order to use in the Hungarian documents and archives the statements with respect to the quintessential scientific results of the dissertation I am going to give the summary in Hungarian as follows.

## Summary of the quintessential results of the dissertation (in Hungarian)

## A disszertáció lényegi tudományos eredményeinek összefoglalás magyar nyelven

Új, illetve finomított nukleoszintézis modellek kidolgozásával és alkalmazásával sikerült javítani az AGB (Aszimptotikus Óriás-ágon levő) csillagokban végbemenő különböző nukleoszintézis folyamatok részleteit és szerepét. Fontos és teljesen új eredménye a disszertációnak az i-folyamat (közepes sebességű neutron befogási folyamat) alapvető szerepének kimutatása az AGB csillagokban. Az alkalmazott modellek megmutatták, hogy az AGB csillagoknak is alapvető szerepe van a csillagközi anyag, illetve a preszoláris-köd – amiből a Nap és a Naprendszer kialakult – a vasnál nehezebb elemekkel való feldúsításában. Ez új paradigma a korábbi, a szupernóvák kizárólagos szerepét figyelembe vevő modellekhez képest. Fontos új megközelítés és eredményei a kutatásnak az AGB csillagokban kialakult vasnál nehezebb elemek azonosítása földi meteorit mintákban.

## Conclusion: judgement by the opponent about the submitted dissertation

**I found that this is a well written and extremely high level academic dissertation which contains unprecedented new results in its scientific discipline. I recommend it to allow for the process of open defense. In case of successful defense of the dissertation I suggest to give for the candidate Dr. Maria Lugaro the title and degree of Doctor of Science of the Hungarian Academy of Sciences (DSc of the HAS).**

10 October 2022
Budapest, Hungary

Imre Tóth
Imre Tóth
DSc HAS
opponent

* * *