Overview

We have published **52 refereed publications** (and 8 submitted, or white paper) as part of the NKFI-K 119517 project between 2016. October 1 and 2020. December 31. Altogether, we have received **3798 citations** to these papers (source ADS, link can be found below) at the time of this writing. Three of these publications are SDSS data release papers, those do now allow acknowledgments of individual grants due to the large number of co-authors. Our PhD student supervised by PI Szabolcs Mészáros and fully funded by this project, László Szigeti, is expected to finish his PhD thesis in the spring of 2021 and defend in the second half of 2021. We have presented our results in SDSS conferences held in 2017, 2018 and 2019. PI Szabolcs Mészáros was an MTA Premium postdoctoral fellow from 2016 to 2019, and has won „The promising researcher of ELTE" fellowship in 2020.

A full list of publications as part of the NKFI-K 119517 project can be found in the following link:

https://ui.adsabs.harvard.edu/user/libraries/cYndK5ZnQG-78lyWWyKZpQ

The major research questions of the original proposal:

"1. How did the first stars in the Milky Way form?
2. What is the connection between multiple populations of stars found based on photometry and chemical composition?
3. What was the process that enriched the interstellar gas with material produced by the first generation of stars?
4. Why the chemical makeup of multiple populations is so different from cluster to cluster?
5. This suggest drastically different formation scenarios, what is the reason of this?"

Research that addresses the project's main questions

1. Overview of 31 globular clusters (GCs): The original goal of my proposal was to make the most complete chemical analysis of as many globular clusters (GCs) as possible in order to gain knowledge of their formation history through the observation of elements Mg, Al, C, N, O participating in the Mg-Al and CNO cycles. This was achieved by using data from the SDSS-IV APOGEE-2 survey, which is capable of observing all bright GCs from both the southern and northern hemisphere using twin spectrographs. Since the instruments, the reduction method and abundance analysis are identical, we were able to study the chemical makeup of multiple populations (MPs) in GCs in a larger scale than it was previously possible and also bring the abundances of southern and northern clusters to the same scale for the first time.

The first step was to update our abundance determination pipeline used by our colleagues at the IAC. In this effort we updated the membership selection and calculated new effective temperatures and surface gravities of the stars in the same 10 northern clusters from Mészáros et al. 2015. We published our first results in **Masseron et al. 2019**. We participated in the discovery of some stars within our most metal-poor clusters that show an extreme Mg depletion and some Si enhancement. At the same time, these stars show some relative Al depletion, displaying a turnover in the Mg-Al diagram. These stars suggest that Al has been partially depleted in their progenitors by very hot proton-capture nucleosynthetic processes.

After years of preparation, the effort of bringing all bright GCs on the same abundance scale was finally achieved in my latest paper, in which I investigated the Fe, Mg, Al, C, N and O abundances of 2283 red giant stars in 31 GCs from high-resolution spectra obtained by the APOGEE-2 survey. **We have published the paper containing the main results of our OTKA proposal in Mészáros et al. 2020**. We reported on the properties of multiple populations based on their Al-Mg, and C-N anti-correlations and also explored the dependence of the abundance spread of Fe, Al and N on cluster properties. These results were presented in the 2019 SDSS virtual conference. To summarize our results, we find the following:

1.) The scatter of Fe does not depend on mass, absolute visual magnitude or age. The uncertainty coming from possible 3D/NLTE and reddening through photometric temperatures does not allows the further refinement of the metallicity scale from the literature. By comparing three independent metallicity scales we determined the uncertainty of [Fe/H] to be +-0.1~dex in the absolute scale.

2.) Other than the well-known Fe spread in ω Cen, we do not observe significant Fe variations in any of the clusters from our sample even though we have the precision to do so. This includes clusters with previously reported Fe spreads: M22, NGC 1851 and M54. While in M22 and NGC 1851 we have more than enough stars to sample multiple Fe populations, in M54 we only observed 7 stars with S/N > 70. We most likely have not sampled enough stars with different Fe abundances possibly due to limitations of the APOGEE fiber collision constraints which limit sampling the inner cluster regions.

3.) By using density maps of the Al-Mg anti-correlations we were able to identify multimodality in several clusters, including M79, ω Cen, and NGC 6752. While ω Cen and NGC 6752 were previously known to host more than two populations based on Al from the literature, M79 has not been previously reported on.

4.) In ω Cen, we observe a turnover of Al abundances for the most Mg-poor stars, similar to that of M15 and M92. Some of these Mg-poor stars are also slightly K enriched compared to standard FG stars drawing a weak K-Mg anti-correlation. However, the weak and blended K lines do not allow us to present a firm discovery of this K enrichment. Follow-up observations are needed to confirm or to contradict our findings.

5.) The ratio of the number of FG/SG stars depends on metallicity and age, but not on mass, which contradicts the findings of Milone et al. (2017). This may be explained by a sample bias created by selecting stars from the outer regions of the clusters (necessary to do to avoid fiber collision) which affects the ratio of FG/SG compared to HST studies which sampled the inner 2 arcminutes of the clusters.

6.) We find a complex relationship between the spread of Al and cluster average metallicity and mass. I identified three distinctive groups in Al scatter - [Fe/H] diagram: 1. clusters with [Fe/H] < -1.3 have a near constant high Al scatter value above 0.4 dex; 2. clusters between -1.0 < [Fe/H] < -1.3 show a wide variety of Al spread; 3. the more metal-rich GCs have a small Al spread, comparable in size to errors. This picture is changed when a correction for the chemical evolution of Al in the Milky Way is introduced. After the correction, the scatter of Al decreases and most of the large step between metal-poor and metal-rich clusters is removed, but the complex nature of the correlation with metallicity remains. The dependence of the scatter of Al with cluster mass is increased suggesting that the extent of Al enrichment as a function of mass was suppressed before the correction.

7.) Metal-rich accreted clusters, NGC 2808 and ω Cen show significantly higher Al scatter than their counterparts formed in situ. The rest of the accreted GCs appear to have similar Al spreads to the in situ clusters.

8.) The measured N-C anti-correlation is generally continuous with some exceptions, NGC 288 and M10 showing clear bimodality. This is in contrast with previous literature observations which generally found bimodal distributions.

9.) The five clusters (47 Tuc, M4, M107, NGC 6388 and M71) that have large variations in N, but Al scatter close to our uncertainties, appear to not show the signs of Mg-Al cycle because their FG stars have elevated [Al/Fe] similar to thick disk stars. Considering that it is necessary to produce significantly more Al to reach the observational limit in the logarithmic abundance scale in metal-rich clusters than in metal-poor clusters, we conclude that our observations of low Al scatter in these five clusters do not rule out the existence of the Mg-Al cycle.

2. Detailed analysis of ω Cen: After finishing the main scientific goals of the original proposal in 2019, we decided to expand on the proposal by carrying out a detailed analysis of ω Cen. **This paper will be submitted to MNRAS in February of 2021**, it is currently sent to SDSS internal review as all SDSS papers must do so.

We studied the multiple populations of ω Cen by using the abundances of Fe, C, N, O, Mg, Al, Si, and K from the high-resolution, high signal-to-noise (S/N>70) spectra of 982 red giant stars observed by the SDSS-IV/APOGEE-2 survey. Our goal was to investigate the formation of ω Cen by determining the chemical makeup and kinematical properties of its multiple populations. We aim to do this by comparing the [Al/Fe] distribution in ω Cen and the Milky Way, and also measure the cluster rotation for each population defined by their Fe, Al and Mg abundances. Based on our findings we conclude the following:

1.) The four metallicity groups found by Johnson & Pilachowski (2010) are confirmed, and we found seven populations based on their [Fe/H], [Al/Fe] and [Mg/Fe] abundances. This confirms the findings of Gratton et al. (2011) by using different elements to trace populations.

2.) We find that the shape of the Al-Mg anticorrelation clearly depends on metallicity, the metal-poor groups ([Fe/H]< −1.2) show continuous, the metal-rich groups ([Fe/H]> −1.2) bimodal distributions.

3.) From the measurements of PA and v_{rot} for all seven populations, the v_{rot} varies from population to population beyond our uncertainties in the most metal-poor group. Some of these observations seem to confirm theoretical calculations by Bekki (2017) stating that SG populations should have a higher rotational velocities than FG ones.

4. We find evidence of that the evolution of Al in the FG stars is very similar to that of thick disk of the Milky Way by comparing the [Al/Fe]-[Fe/H] distribution of ω Cen with that of our Galaxy. We believe the similarity is not the result of an interaction with the thick-disk, but rather of internal evolution, because stars with thick-disk like Ce and C+N+O abundances are not observed.

5. Both the PA and vrot of the most metal-rich population, P7 is larger than the rest of the populations. While the difference is relatively small, it is larger than the calculated uncertainties. These observations, along with their position inside the cluster based on literature, may suggest that the most metal-rich group, P7 is a result of a possible merger with gas that originated from the halo.

6. We report that the N-C anticorrelation also depends on metallicity, similarly to the Al-Mg anticorrelation. The distribution is continuous up to $[Fe/H] < -1.2$, then becomes bimodal at higher metallicities.

7. The two populations have different [C/N] values. We may observe a slight positive correlation between [C/N] and metallicity in the FG stars.

8. The increased C+N+O with increased metallicity previously found in the literature is confirmed.

3. Photometric study of GCs: In **Mészáros et al. 2018** we described the first main results of my original research proposal, which was the study of the photometric and spectroscopic properties of multiple populations in seven northern globular clusters (GCs). We employed precise ground based photometry from the private collection of Stetson, space photometry from the Hubble Space Telescope, literature abundances of Na and O, and APOGEE survey abundances for Mg, Al, C, and N. Multiple populations were identified by their position in the CU,B,I -V pseudo-CMD and confirmed with their chemical composition determined using abundances. We confirmed the expectation from previous studies that the RGB in all seven clusters are split and the different branches have different chemical compositions. We found that there is no one-to-one correspondence between the Mg-Al anticorrelation shape (bimodal vs. continuous) and the structure of the RGB seen in the HST pseudo-CMDs, with the HST photometric information usually implying more complex formation/evolution histories than the spectroscopic ones. We also reported on finding two second generation HB stars in M5, and five second generation AGB stars in M92, which is the most metal-poor cluster to date in which second generation AGB stars have been observed. While most of this research was finished during the first year, the publication of this paper was finalized in 2018. We presented these results in a talk at the SDSS conference in Soul, South-Korea (18 to 22 June, 2018).

4. Formation scenarios of GCs: As part of a research group at the IAC, we worked on finding out which polution model is the most responsible for the evolution of multiple population of stars in (**Dell'Agli et al. 2018**). We discussed the self-enrichment scenario by asymptotic giant branch (AGB) stars for the formation of multiple populations in GCs by analysing data set of giant stars observed in nine Galactic GCs, covering a wide range of metallicities and for which the simultaneous measurements of C, N, O, Mg, Al, and Si are available. We found that the AGB yields can reproduce the set of observations available, most importantly the observed trend with metallicity, which agrees well with the predictions from AGB evolution modelling. The present results confirm that the gas ejected by stars of mass in the range $4\ M_{\odot} \leq M \leq 8\ M_{\odot}$ during the AGB phase share the same chemical patterns traced by stars in GCs. This further supports the that AGB stars were the key players in the pollution of the intra-cluster medium, from which additional generations of stars formed in GCs. Understanding which pollution model describes the formation of multiple populations was one of the main goals of my research proposal, and our study is the first that can prove the nature of polluters with great certainty.

5. Rotation of GCs: As part of László Szigeti's PhD project, he analyzed 10 globular clusters in order to measure their rotational properties by using high precision radial velocity data from the SDSS-IV APOGEE-2 survey. Out of the 10 clusters we were able to successfully measure the rotation speed and position angle of the rotation axis for 9 clusters (M2, M3, M5, M12, M13, M15, M53, M92, M107). We used M5, a very well-studied cluster, to assess the accuracy of our method and find very good agreement between our values and that of the literature. For four of the globular clusters, M3, M13, M5 and M15, we separated the sample into two generation of stars using their [Al/Fe] abundances and examined the kinematic features of these generations separately from one another. In case of M3, we found significant difference between the rotational properties of first and second populations, confirming for the first time the predictions of several numerical simulations from the literature. The other three clusters (M5, M13, M15) also show smaller deviation between the two groups of stars, but those deviations are comparable to our errors. **The paper describing these results have been submitted to MNRAS in January of 2021.**

Additional scientific results

1.) The Ariel space mission designed for optical and infrared spectroscopic and photometric observations will be the most important instrument of the European exoplanet research in the decade of 2030s. Our international working group led by Gothard Astrophysical Observatory of Eötvös Loránd University has studied the technical description and application possibilities of the precise high resolution photometry in time domain. On 10th November 2020 ESA accepted the space telescope's program based on the Red Book, which was submitted in October 2020. The related scientific papers will appear in a dedicated Ariel volume of Experimental Astronomy in 2021 (Szabó et al.,2021 Borsato et al. 2021).

2.) In 2019 and 2020 we continued to work on the preparations of APOGEE next data release, DR16, published at the end of 2020. This was done by implementing an interpolation code to fill in the holes in the model atmosphere grid, explained in Jönsson et al. 2020. This had a profound effect on the shape of the HRD observed by APOGEE below 4000K, a result that will be published in a later paper going along with DR16.

3.) Szabolcs Mészáros participated in the detailed comparison between APOGEE and LAMOST (Anguiano et al. 2019). We undertook a critical and comprehensive comparison of the radial velocities and the main stellar atmosphere parameters for stars in common between the latest data releases from the Apache Point Observatory Galaxy Evolution Experiment (APOGEE) and the Large sky Area Multi-Object Spectroscopic Telescope (LAMOST) surveys.

4.) Szabolcs Mészáros participated in the creation of the second APOKASC Catalog (Pinsoneault et al. 2019), which contains stellar properties for a large sample of 6676 evolved stars with APOGEE spectroscopic parameters and Kepler asteroseismic data analyzed using five independent techniques. Our data include evolutionary state, surface gravity, mean density, mass, radius, age, and the spectroscopic and asteroseismic measurements used to derive them.

5.) Gyula Szabó and Szabolcs Mészáros participated in preparing the detailed science case of the Maunakea Spectroscopic Explorer (The MSE Science Team et al. 2019, Bergemann et al. 2019). MSE will unveil the composition and dynamics of the faint Universe and impact nearly every field of astrophysics across all spatial scales, from individual stars to the largest scale structures in the Universe.

6.) Szabolcs Mészáros participated in the study of internal mixing on the giant branch (Shetrone et al. 2019). We used [C/N] abundances in 26,097 evolved stars from the SDSS-IV/APOGEE-2 Data Release 14 to trace mixing and extra mixing in old field giants with $-1.7 < [Fe/H] < 0.1$

7.) Alíz Derekas lead a research group that confirmed the binary nature of the hybrid pulsator KIC 5709664 found with the frequency modulation method (Derekas et al. 2019).

8.) Gyula Szabó studied the dependence of sub-Jupiter/Neptune desert of exoplanets on stellar parameters (Szabó et al. 2019).

9.) Similarly to the first year, we continued to work on the APOGEE reduction pipeline by participating in the calibration and validation of APOGEE DR13 and DR14 data. (Jönsson et al. 2018, Holtzmann et al. 2018). We studied the behaviour of individual abundances measured in GC stars when compared to literature. We discovered that the pipeline measures the wrong O abundances for second generation stars, which culminates in an unwanted O-effective temperature degeneracy (Jönsson et al. 2018). We implemented and tested an irregular interpolator in the first year in order to fill in the holes in the flux grid used to compare the observed spectra to. These holes, where we have no flux information for certain atmospheric parameters (Teff, logg, metallicity), affect the quality of the derived parameters of tens of thousands of stars and have been a problem for the APOGEE team since 2012. This interpolation algorithm was implemented into APOGEE's reduction pipeline between July and August 2018 and is part of DR16. We presented this algorithm in a talk at the SDSS conference in Soul, South-Korea (18 to 22 June, 2018). This work is part of an official SDSS technical paper next year, Jönsson et al. 2020.

10.) László Szigeti, who is fully funded by this OTKA project started his PhD fellowship at ELTE this September. Carbon isotope ratios, along with carbon and nitrogen abundances, were derived in a sample of 11 red-giant members of one of the most metal-rich clusters in the Milky Way, NGC 6791 in order to test the effects of deep mixing and its effect on stellar evolution. The derived 12C/13C ratios are in very good agreement with the final isotopic ratios from thermohaline-induced mixing models. Our results suggest that extra mixing is stronger at higher metallicities, but it also depend on the evolutionary status of selected stars. While most of the research were done in the first year, we published the paper describing these results in **Szigeti et al. 2018.**

11.) In Röser et al. 2018, we were searching for new open clusters or moving groups in the solar neighbourhood by using the Gaia-TGAS catalogue. We examined stars forming over-densities in optical and near-infrared colour-magnitude diagrams to determine if they are compatible with isochrones of a cluster. We detected a hitherto unknown moving group or cluster in the Upper Centaurus Lupus (UCL) section of the Scorpius-Centaurus OB association (Sco-Cen) at a distance of 175 pc from the Sun. It is a group of 63 co-moving stars of less than 10 to about 25 Myr in age.

12.) We continued to work on the APOGEE reduction pipeline by collecting stars from the literature that will be observed by APOGEE (Zasowski et al. 2017) and by implementing an irregular interpolator in order to fill in the holes in the flux grid used to compare the observed spectra to. These holes, where we have no flux information for certain atmospheric parameters (Teff, logg, metallicity), affect the quality of the derived parameters of tens of thousands of stars and have been a problem for the APOGEE team since 2012. We developed a radial basis function interpolator in C. The error of this interpolator is in the order of 1-2% in normalized flux, which is remarkable, especially considering that we can achieve this accuracy even if 20-30% of the total models are missing. As APOGEE will have no data release in next SDSS data release, these improvements have to be made by 2019. We presented our results in a talk at the SDSS conference in Santiago de Chile, Chile (22 to 29 July, 2017). We were working with our collagues from the IAC, Tenerife, Spain to develop tests to estimate its accuracy, and to organize its implementation into the main reduction software of APOGEE, which will happen next year. We also performed a number of tests related to consistent model atmospheres at the IAC, and determined which element requires a unique model atmosphere before any synthesis. This work will result in an official SDSS technical paper next year.

13.) In cooperation with scientists from the Space Telescope Science Institute (STScI), we lead a team that computed synthetic spectra for a total of 312 different compositions that were selected to cover the majority of actual stellar abundances, 13 [M/H], 6 [C/M], and 4 [α/M] steps, and temperatures between 30,000 and 3,500K (Bohlin & Mészáros et al. 2017). This new comprehensive set of model atmospheres are now publicly available through the MAST12 (https://archive.stsci.edu/prepds/bosz/) at the STScI and have a wavelength coverage of 0.1–32 μm. These models will be essential to the flux calibration and interpretation of stellar spectra from the successor of the Hubble Space Telescope, the James Webb Space Telescope. I issued a press release of this work on the 15th of June, which was published on the website of the Hungarian Academy of Sciences, and also on all the main Hungarian press sites (Index, Origo, etc.).

14.) We used the 200 × 200 pixel `superstamp' images of the centres of the open clusters NGC 6791 and NGC 6819 taken by the Kepler space telescope to identify and study many variable stars that were not included in the Kepler target list (Drury et al. 2017). KIC 2569073 (V = 14.22), is a particularly interesting variable Ap star that we discovered in the NGC 6791 superstamp. Colour photometry revealed an antiphase correlation between the B band, and the V, R and I bands. This Ap star is a rotational variable, and is one of only a handful of Ap stars observed by Kepler. While no change in spot period or amplitude is observed within the 4 yr Kepler time series, the amplitude showed a large increase compared to ground-based photometry obtained two decades ago.

15.) To investigate low-amplitude irregularities in the pulsations of Cepheid stars, we obtained photometry of two Cepheids, using the MOST space telescope (Molnar et al. 2017). The data revealed alternations in the amplitudes of cycles in V473 Lyr, the first case of period doubling detected in a classical Cepheid. In U TrA, we tentatively identified one peak as the 0.61-type mode often seen in conjunction with the first radial overtone in Cepheids, but given the short length of the data, we could not rule out that it is a combination peak instead. Simultaneous ground-based photometry and spectroscopy yielded the phase lag parameter of a second-overtone Cepheid for the first time. We found no evidence for a period change in U TrA. Period doubling in V473 Lyr provided a strong argument that mode interactions do occur in some Cepheids.

16.) We presented a detailed analysis of the bright Cepheid-type variable star V1154 Cygni using 4 yr of continuous observations by the Kepler space telescope (Derekas et al. 2017). We detected 28 frequencies using the standard Fourier transform method. We identified modulation of the main pulsation frequency and its harmonics with a period of ~159 d. We detected another modulation with a period of about 1160 d. The star also showed significant power in the low-frequency region that we identified as granulation noise. We obtained new radial velocity observations that are in a perfect agreement with previous years data, suggesting that there is no high-mass star companion of V1154 Cygni. Finally, we discussed the possible origin of the detected frequency modulations.