SCOPES 2014 -2016

Guidelines for scientific reports (JRP/IP)

The report must be submitted to the SNSF by the project coordinator (**electronically and in print**). It should cover **the whole period since the start of the project**.

1. General Information

1.1 **Title of the JRP/IP: Stars, Stellar Explosions, and the Origin of the Elements (Scientific Report 2015/2016)**

1.2 **Number of the JRP/IP: IZ73Z0_152485**

1.3 Name of co-ordinator and partner teams:

Principal Applicant: Thielemann, Friedrich-K., Basel

Co-applicants:

Charbonnel, Corinne; Meynet, Georges; Jablonka, Pascale, Versoix/Geneva

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2. Overview of (research) activities

2.1 Which work has been carried out by each of the teams?

Have the activities been in accordance with the scientific and technical description in the application?

The summary of the original proposal described a number of related topics from nuclear input, over stellar evolution and explosions, the ejecta composition of stellar winds and explosions, the role of their remnants, and finally the impact on the evolution of galaxies. Integrated over the whole grant period we achieved essential progress in all topics of the project and have even gone beyond the initial expected outcome in these major research directions:

- Nuclear Input for stellar modelling and nucleosynthesis

- Investigation of stellar evolution and supernovae and other stellar explosions

- Abundance determination and chemical evolution of galaxies

These included a number of global objectives:

1. provide nuclear data for neutron-rich heavy nuclei (including superheavies)
2. neutrino transport and hydrodynamic explosion models
3. tests of nuclear data in nucleosynthesis calculations for real scenarios and existing experiments
4. set up atomic input for accurate modelling of heavy element spectra
5. analyse observational spectra in order to provide an abundance data base as a function of metallicity
6. combine nucleosynthesis predictions with chemical evolution models and compare to observations
7. predict light curves and spectra of supernova models for NLTE conditions and at shock break-out and other NLTE effects

8. an effective algorithm for simulating SN light curves will be developed for cases important in cosmology
9. model turbulent flame propagation in SNIa
10. obtain constraints on the parameters of dark energy

which have been worked out in more detailed subprojects (listed with the milestone numbers of the original proposal):

(1) Hydrodynamic (neutrino-)radiation transport calculations of core-collapse supernovae with new presupernova models (milestone 2)

(2) Numerical simulations of shock-breakout in supernovae, based on multigroup radiation transfer, coupled to hydrodynamics (milestone 7b)

(3) Neutrino-induced nucleosynthesis and the influence of neutrinos on the production of nuclei beyond Fe in proton-rich environments in the innermost ejected zones, as well as on the outer zones dominated by neutrino-nuclear spallation

(4) Equation of state descriptions at extreme densities, combining the quark-hadron phase transition, an excluded-volume approximation, as well as the inclusion of light clusters, were developed for the implementation in supernova simulations (milestone 2 and additional activities beyond originally planned tasks)

(5) Extension of the calculations until late times when the neutrino-driven wind provides conditions which might possibly support an r-process to produce the heaviest nuclei, and testing alternatives like polar jet-ejection in rotating models, including magnetohydrodynamic effects (milestone 3b)

(6) Consistent r-process calculations for the main r-process scenario which include fission and testing the influence of nuclear masses/fission barriers and other predictions of nuclear properties on the formation of superheavy elements (milestone 3b)

(7) Using phenomenological approaches to spontaneous fission and its application to the r-process. Testing the influence of models for spontaneous fission rates and other predictions of nuclear properties on the formation of superheavy elements (milestones 1 and 3a)

(8) Modeling of non-LTE line formation for heavy elements in stellar atmospheres (milestones 4,7a)

(9) Determination of element abundances in old stars over a large range of metallicities, and thus providing a data base for changes in abundance ratios of heavy (neutron-capture) elements during the evolution of the Galaxy (milestone 5)

(10) Determination of stellar ages for different metallicities via the decay pattern of actinide abundances (milestone 5)

(11) Galactic chemical evolution calculations, based on the ejected abundance yields from the nucleosynthesis predictions, and comparison with observations obtained from our investigations; testing the enrichment pattern of stellar populations in the Galaxy at different evolutionary times and distances (milestone 6 and 5)

(12) Elaborating new methods for cosmology, such as the Dense Shell Method, and obtaining constraints on the parameters of dark energy (milestones 8,10)

(13) flame front behavior investigations in SNIa and study of a flamelet regime of turbulence (milestone 9)

We list the detailed milestones of the original proposal, the expected duration, the partners involved and responsible as well as which fractions of the initially suggested subprojects have been achieved during the project:

Milestone	**Associated activity**	**Expected duration**	**Responsible project partner**	**Realized percentage after 2nd year**
1a	Strength function model	years 1,2	Partner 1,3	~100
1b	Beta-decay rates and probabilities of beta-delayed processes	years 1,2	Partner 1,3	>100
2	Neutrino transport and supernova models	years 1,2,3	Partner 1,3	~100
3a	Tests for nuclear data and impulse nucleosynthesis	years 2,3	Partner 1,3	100
3b	Nucleosynthesis in consistent models	years 1,2,3	Partner 1,3	>100
4	Atomic input for spectrum modelling	years 1,2	Partner 2,3,4	100
5	Abundance determination from spectra	years 1,2,3	Partner 2,3,4	>100
6	Incorporation of nucleosynthesis predictions in chemical evolution models	Years 1,2,3	Partner 1,2,4	>100
7a	Different NLTE effects	Years 1,2	Partner 3,4	100
7b	Shock-breakout with relativistic effects	Years 1,2	Partner 1,3	100
8	New direct method for cosmology with multi-dimensional photon transport	years 1,2,3	Partner 3	~100
9	Turbulent flame propagation in SNIa	years 1,2,3	Partner 3	~100
10	obtaining constraints on the parameters of dark energy	years 2,3	Partner 3	~100

*** 1=Basel; 2=Geneva; 3=Russian partner; 4=Ukrainian partner**

In general the detailed plan for the duration of the project was accomplished in all major points, in fact partially overaccomplished due to a six months extension, and the main results are pointed out below. The last column of the Table shows this in more detail. Some subprojects were carried out additionally to the project plan (like the synthesis of elements in astrophysical plasmas with very strong magnetic fields; NLTE corrections for lines of Ba II; abundances of P, S, and Sr were derived from the infrared spectra of three stars; spectroscopic studies of four southern-hemisphere G-K supergiants; discovery of blue companions to two southern Cepheids). In some cases progress was a bit slower than expected, but attained with the aid of the six months extension after the end of the 3rd year, in other cases the progress and results obtained superseded our expectations.

We do not provide the detailed achievements of the Basel and Geneva groups in this document, they are given in the reports for their individual SNF grants. But the major results, ***which relate to this combined SCOPES project****, are listed in the bibliography, and relate to nuclear input data, stellar modeling (including rotation, instabilities and mixing, s-process predictions, wind ejecta, and pre-supernova models), multi-D modeling of core-collapse and other supernovae, binary mergers/collisions, nucleosynthesis predictions, and their implementation in galactic evolution, plus comparison with observations (related to milestones 1, 2, 3b, 5, 6, and 9). This was also reported in invited talks and contributions to major international conferences and workshops. For the Basel group the most important ones were Nuclear Physics in Astrophysics (in York, 2015), Nuclei in the Cosmos (in Niigata, Japan, 2016,) as well as NPCSM (in Kyoto, Japan, 2016), Nuclear Astrophysics in the Gravitational Wave Astronomy Era (in Trento, Italy, 2017), the Progenitor Supernova Remnant Connection (Ringberg, Germany, 2017), and Stellar Evolution, Supernova Explosions, and Nucleosynthesis across Cosmic Time (in Tokyo, 2017). While the Geneva groups were partially* *present at these meetings as well, their main (and truly impressive) showing was demonstrated by the invited talks and contributions to the International Astronomical Union Meeting (in Honolulu, 2015), the Texas Conference on Relativistic Astrophysics (in Geneva, 2015) and the EWASS (European Week of Astronomy and Space Science) meetings in 2016 (Athens) and 2017 (Prague).*

The Russian groups had also major contributions at the Niigata, Ringberg, and Toyko meetings (see above), while the Ukrainian groups did so for the York, and EWASS meetings, but a much more detailed list of conference attendances is given further below. In addition to individual visits, and joint participations in the above mentioned conferences, our collaboration organized two joint meetings, one in Basel (Brainstorming and Fun: Compact objects, their equation of state, related explosive events, and their nucleosynthesis) in September/October 2016 and a final meeting in Moscow (Galactic chemical evolution and Heavy elements nucleosynthesis) in July 2017.

The accomplishments of the Russian and Ukrainian groups (mainly concentrating on the final years 2016/2017, see also the earlier 2015/2016 report) are listed below in detail:

I. Investigations in stellar evolution and supernovae

(1) Hypernovae and red novae ***(Baklanov, Blinnikov, Glazyrin, Potashov)***

Some joint results on radiation-hydrodynamics were produced (main investigationss were done by **S. Blinnikov, P. Baklanov, M. Potashov and S. Glazyrin**.) for the strongest explosions, accessible by the STELLA code: hypernovae, and very weak explosions: red novae (with luminosities between nova and supernova outbursts). The results are published in two papers in *MNRAS* with acknowledgement of SCOPES grant.

The main interest was in modeling Superluminous Supernovae (SLSNe) for their applications in cosmology. Hypernovae are not extremely luminous, but they have high kinetic energy of explosion. In our paper (Alina Volnova, et al. 2017. Multicolour modelling of SN~2013dx associated with GRB130702A. MNRAS 467, 3500) the afterglow of GRB130702A with bumps in the light curve is interpreted as a hypernova SN2013dx.

Parameters of hypernova SN2013dx model

The optical observations of SN 2013dx, related to the Fermi burst GRB 130702A, which occurred at redshift z = 0.145 were presented. It is the second-best sampled gamma-ray burst (GRB)/supernova (SN) after SN 1998bw. The observational light curves contain more than 280 data points in the uBgrRiz filters until 88 days after the burst. The multicolour light curves were modelled numerically using the one-dimensional radiation hydrodynamical code STELLA, previously widely implemented for modelling typical non-GRB SNe. The best-fitting model has the following parameters: pre-SN star mass M = 25 M_sun; mass of the compact remnant (black hole) MCR = 6 M_sun total energy of the outburst Eoburst = 3.5×10^{52} erg; pre-supernova star radius R = 100 R_sun; M_56Ni = 0.2 M_sun, which is totally mixed through the ejecta; MO = 16.6 M_sun; MSi = 1.2 M_sun and MFe = 1.2 M_sun, and the radiative efficiency of the SN is 0.1 per cent. First year light is about 0.03 foe (Bethe) while for SLSNe it is up to 1~foe. Important is the large BH mass needed for explaining the light curve.

We reported (V.Lipunov et al. 2017, accepted) the discovery and multicolor (VRIW) photometry of a rare explosive star MASTER OT J004207.99+405501.1 - a luminous red nova - in the Andromeda galaxy M31N2015-01a. The original light curve acquired with identical MASTER Global Robotic Net telescopes in one photometric system was used: VRI during first 30 days and

W (unfiltered) during 70 days. We also added published multicolor photometry data to estimate the mass and energy of the ejected shell, and discuss the likely formation scenarios of outbursts of this type. We propose the interpretation of the explosion to be consistent with the evolutionary scenario where star merger is a natural stage of the evolution of close-mass stars and may serve as an extra channel for the formation of nova outbursts.

Parameters of Red Nova in M31

It is important that the entire observational part of the study was performed on identical telescopes equipped with identical photometers. The resulting light curve agrees fairly well with the independent light curve published by Kurtenkov et al. (2015). However, our interpretation led us to infer a relatively higher total progenitor mass. The rather long plateau (50 days) requires a higher merged stellar mass (3 solar masses). The corresponding explosion energy should be lower $2.5 \cdot 10^{50}$ erg , whereas the total kinetic energy of the ejected envelope is lower by three orders of magnitude. The proposed interpretation of the explosion is consistent with the proposed evolutionary scenario where star merger is a natural stage of the evolution of close-mass stars and may serve as an extra channel for the formation of nova outbursts.

(2) *Superluminous supernovae* ***(Glazyrin, Blinnikov, Baklanov)***

Superluminous supernovae (SLSNe) are outstanding objects, whose dynamics are not fully understood. One scenario that describes such objects is related to radiatively cooling shock waves. Modeling of such shock waves requires correct radiation-hydrodynamics simulations. Our group develops such multi-dimensional numerical tools to study SLSNe thoroughly (and other astrophysical problems). First studies have shown that even in optically thin regime (when radiation transfer leads to volumetric energy losses) the dynamics of the shock wave becomes nontrivial: the dense shell is formed, and in some cases it becomes unstable. We model the supernova-like RCS-s with various codes (well-known in astrophysical community FLASH, PLUTO, and our developed FRONT3D) in different physical (kinds of ambient media, implied symmetry, inclusion of magnetic fields) and calculation setups.

In pure hydrodynamics on Cartesian grids the dense shells show strong “spontaneous” bending and successive fragmentation soon after their formation, but remain almost unperturbed on polar meshes. We explain this by physical Rayleigh–Taylor like instabilities triggered by numerical noise (however, they are sensitive to physical perturbations of the ambient medium as well). Conditions for such instabilities follow both from the shell structure itself and from episodes of transient acceleration during re-establishing of dynamical balance after the sudden radiative cooling onset. The Non-linear Thin Shell Instability (Vishniac 1994) appears excited efficiently only by rather peculiar radial pattern of fluctuations (like in Blondin et al. 1998) and seems to have only limited chances to develop in real supernova remnants (SNRs). The results of these studies were published in **Badjin et al. MNRAS (2016**) paper.

Further studies include additional physics: more correct cooling functions and ambient magnetic fields. These effects could significantly influence the structure of the shock wave, most of all, moderate the dense shell compression and pressure-density contrasts therefore decreasing the largest growing mode wavelength considerably. Our simulations show the importance of these effects and propose some criteria for relevant contribution of these effects. Though, in real situations (e.g. for Galactic fields B~1 μG) the shock wave is significantly perturbed, our high-resolution simulations show that conditions for instability remains.

The work has great importance for SLSN because any perturbations of radiatively-dominated shock waves could influence the radiation efficiency and therefore their light-curves.

The peculiarity of PTF12dam - superluminous supernova

Dense Shell Method (DSM) is a new direct method of determining the distance to supernovae.

The DSM is based on the observations of the radiation from the shock wave in the interaction of the ejected supernova matter and the previously ejected massive dense circumstellar envelope.

In our previous research with the support of SCOPES we constructed the interaction model and simulated the light curves for superluminous supernova – PTF12dam. After the shock breakout, the model light curves drop sharply due to the lack of additional energy sources. The further observations of PTF12dam indicated that there was no sharp drop in the light curves. It's means that we were missing something in our models and they require additional research.

In the paper by A. **Tolstov et al. 2017**, we propose that PTF12dam is powered by a double energy source: radioactive decay of 56Ni and a radiative shock in a dense circumstellar medium. To describe multicolor light curves and spectra,we use radiation-hydrodynamics calculations of the STELLA code. We found that light curves are well described in the model with 40 Msun ejecta and 20–40 Msun circumstellar medium. The ejected 56Ni mass is about 6 Msun, which results from explosive nucleosynthesis with large explosion energy 20–30 FOE. In comparison with alternative scenarios of pair-instability supernova and magnetar-powered supernova, in the interaction model, all the observed main photometric characteristics are well reproduced: multicolor light curves, color temperatures, and photospheric velocities.

*(3) Supernovae (**Potashov, Blinnikov, Baklanov**)*

The photospheric phase in supernova explosions

The importance of allowance for the time-dependent effect in the kinetics at the photospheric phase during a supernova explosion has been confirmed by several independent research groups. The time-dependent effect provides a higher degree of hydrogen ionization in comparison with the steady state solutions and strengthens the Ha line in the resulting simulated spectrum, with the intensity of the effect increasing with time. However, some researchers argue that the time-dependent ionization effect is unimportant. Its allowance leads to an insignificant strengthening of Ha in their modeling only in the first days after explosion.

The developed earlier software package LEVELS (**Baklanov, Blinnikov, Potashov, Dolgov, 2013**) for the calculation of the populations of the levels of all atoms and ions in the complete kinetic scheme, where the radiation field is described in the Sobolev approximation was modified to take into considerations the time-dependent effect in the kinetics at the photospheric phase during a supernova explosion.

The former realization of LEVELS, used to evaluate the time-dependent ionization in the envelopes of type II supernovae at the photospheric phase (**Potashov et al. 2017)** was taken into account approximate number densities of iron admixtures.

The current code was modified by a self-consistent inclusion the metals in the complete kinetic scheme. With such a modification, there were considered the hydrogen envelope with l-equilibrium approximation with iron admixtures. The self-consistent solution, produced on the basis of development approach for this most realistic case, let us conclude that emission in Hα profiles in the steady-state increases while emission in time-dependent decreases. So the time-dependent effect is weakened but does not disappear completely. Consequently, the abundance of iron (and other metals capable of absorbing Lα) in the SN envelope is an important factor affecting the intensity of the time-dependent effect.

We have confirmed that time-dependent effect in the envelope of SN II during photosphere phase is important. (**the paper** "Some problems in spectral modelling of pulsational pair instability SN 2006gy" **is in preparatio**n).

*(4) Hybrid stars and phase transitions (**Yudin, Hempel, Nadyozhin, Thielemann)***

Some specific properties of hybrid stars, i.e. compact stars which contain the core made of quark matter were explored. It was shown that the unusual thermodynamic properties of matter within the region of two phase coexistence in hybrid stars result in a change of the standard condition for beginning of convection. In particular, the thermal flux transported by convection may be directed towards the stellar centre. Favorable circumstances leading to such an effect of 'inverse convection' and its possible influence on the thermal evolution of hybrid stars was explored. The possible influence of this effect on the supernova's properties was considered. In particular, if the 'inverse' convection appeared already in the early post-bounce phase of the supernovae, it could also impact the explosion dynamics. (**Yudin, Hempel, Nadyozhin, Razinkova, 2016)**.

A phase transition to quark matter can lead to interesting phenomenological consequences in core-collapse supernovae, e.g., triggering an explosion in spherically symmetric models. However, until now this explosion mechanism was only shown to be working for equations of state that are in contradiction with recent pulsar mass measurements. Here, we identify that this explosion mechanism is related to the existence of a third family of compact stars. For the equations of state investigated, the third family is only pronounced in the hot, early stages of the protocompact star and absent or negligibly small at zero temperature and thus represents a novel kind of third family. This interesting behavior is a result of unusual thermal properties induced by the phase transition, e.g., characterized by a decrease of temperature with increasing density for isentropes, and can be related to a negative slope of the phase transition line in the temperature-pressure phase diagram. (**Hempel et al., 2016**).

The variational principle for stars with a phase transition has been investigated. The term outside the integral in the expression for the second variation of the total energy of a star is shown to be obtained by passage to the limit from the integration over the region of mixed states in the star. The form of the trial functions ensuring this passage has been found. All of the results have been generalized to the case where general relativity is applicable. The known criteria for the dynamical stability of a star when a new phase appears at its center are shown to follow automatically from the variational principle. Numerical calculations of hydrostatically equilibrium models for hybrid stars with a phase transition have been performed. The form of the trial functions for the second variation of the total energy of a star that describes almost exactly the stability boundaries of such stellar models is proposed. (**Yudin, Razinkova, and Nadyozhin, 2017**).

We performed a global study of light asymmetric clusters effect for the supernova matter conditions. One of our most peculiar finding is a high abundance of ^{4}H isotope which was not taken into account previously. We explore a wide domain of thermodynamic parameters, representative for the matter of collapsing stellar core on infall stage of collapse as well as during post-bounce phase. It appears that for light nuclei it is important to use exact information about it's properties (values of spins and energies of known excited states) to obtain a reliable EoS. For the heavy nuclei the effect of the whole partition functions occurs to be of the same importance. By comparison of three EoSs with different underlying physics we ensured the stability of light clusters effect for various conditions. Besides we discussed the domains in supernova modelling where the light nuclei effect can has most important consequences. The importance of light clusters for neutrino–matter interaction rates is also discussed. (**Yudin et al., sent to MNRAS**).

*(5) Stellar Velocity Dispersion in Galaxies and Dark Energy (**Shchelkanova, Blinnikov)***

To understand correctly Dark Energy (DE) evolution in the Universe, one has to investigate the evolution of Dark Matter (DM). Galina A. Shchelkanova, former PhD student of Blinnikov, studies DM distribution in nearby galaxies based on the observations of stellar velocity dispersion obtained from Kohey Hayashi. The data are taken from Hayashi, Cihiba (2015) and Hayashi et al. (2016).

In those papers the galaxies were modelled via quasi-hydrodynamic approach (Jeans equations), while G.Shchelkanova constructs them in collisionless N-body self-consistent disk-bulge-halo modeling. In her last work (paper in preparation) she has built a near equilibrium model of the Fornax dwarf galaxy using mkkd95 code (available in NEMO package) described in Kuijken, K., Dubinski. J., 1995, MNRAS, Vol. 277. This code does not rely on dynamical evolution of the system and thus allows one to obtain equilibria of galaxies which may be unstable (contrary to many other codes which are based on relaxation to stable equilibrium).

Fornax galaxy model components for mkkd95 used up to 1.5 million of particles in DM Halo and in the stellar bulge. Stellar component assumed oblate Plummer profile, constant velocity anisotropy parameter fitting to the observed velocity dispersion profile. Dark matter component assumed either axisymmetric core or cusped profiles. This procedure allows to get the evolution of the two component near equilibrium galaxy model. The dynamical N-body simulation of the obtained model with gyrFalcON code has shown a stable behaviour.

Among other parameters for this galaxy a rather low mass-to-luminosity ratio was obtained for the stellar component, M/L ~ 1.0. This value agrees within error bars with those found by absolutely different method in Jardel, J.R., Gebhardt, K. (2012. The Dark Matter Density Profile of the Fornax Dwarf. The Astrophysical Journal 746, 89**. (G. Shchelkanova, S. Blinnikov. "N-body self-consistent star-bulge and** DM-halo modeling of Fornax dwarf galaxy", **in preparation).**

II. Nuclear Input for stellar modelling and nucleosynthesis

*(1) Theoretical and Experimental Nuclear Investigations (**Lutostansky, Panov**)*

Delayed fission and odd-even anomaly in the thermonuclear explosions yields

In the framework of the adiabatic binary model, calculations of yields for heavy transuranium nuclei production were made for the "Mike", "Par" and "Barbel" thermonuclear explosions, performed in USA. It has been shown that previously observed effect of even-odd anomalies in the yields of nuclei with $A = 250$ - 255 can be explained predominantly by the effect of beta-delayed fission. That is when pigmy resonance in the beta- strength function appears in the energy window of the beta-decay of these short-lived neutron-rich nuclides. In this case the corresponding probabilities increase strongly and the concentration of the corresponding nuclides decreases, which leads to the elimination of even nuclides with respect to mass number *A*. Thus, we can see the domination of odd *A* nuclei – odd-even anomaly in the yields of thermonuclear explosions. **(Lutostansky, Tikhonov, 2017)**

Intense Antineutrino Source Based on a Lithium Converter. Proposal for a Promising Experiment for Studying Neutrino Oscillations

An intense electron-antineutrino source with a hard spectrum (E_{max} = 13 MeV and = 6.5 MeV) can be created on the basis of the short-lived isotope ^{8}Li (β^--decay, $T_{1/2}$ = 0.84 s) formed via the (n, γ) activation of ^{7}Li. In contrast to a reactor antineutrino spectrum whose uncertainty is large, particularly in the high-energy region $E_\nu > 6$ MeV, which is experimentally relevant, the lithium spectrum is accurately determined. The proposed accelerator-driven experimental scheme with a neutron-producing target and a lithium converter as an intense source is an alternative to a nuclear reactor. The required amount of high-purity ^{7}Li will be reduced in many times by using the suggested heavy-water LiOD solutions. A possible experiment involving the lithium source on search for sterile neutrinos in the mass region $\Delta m^2 \geq 0.2$ eV^2 with a very high sensitivity to mixing-angle values down to sin2(2Θ) ≈ (7–10) × 10^{-4} at the 95% C.L. has been considered. **(Lyashuk, Lutostansky, 2016)**

Resonances in the strength function of charge-exchange excitations and processes accompanying the beta decay of neutron-rich nuclei

Energies of the giant Gamow-Teller and analog resonances – E_G and E_A, respectively, – were calculated within the microscopic theory of finite Fermi systems. These resonances dominate in the strength function of the charge-exchange excitations of atomic nuclei.
The calculated energy difference $\Delta E_{G-A} = E_G - E_A$ tends to zero with A in heavy nuclei indicating the restoration of Wigner SU(4)-symmetry. The calculated ΔE_{G-A} values are in good agreement with the experimental data. The average deviation is $\delta(\Box\varepsilon) \leq 0.30$ MeV for the 33 considered nuclei where experimental data are available. This deviation is much better than calculations by other methods and is commensurate with the accuracy of experimental data on E_{GTR}. The ΔE_{G-A} values were investigated for very heavy and superheavy nuclei up to the mass number $A = 290$.
Charge-exchange states, the so-called “pigmy” resonances, which are below the giant Gamow–Teller resonance, have been studied in the self-consistent theory of finite Fermi systems. Microscopic numerical calculations and semi-classical calculations were presented for nine tin isotopes with the mass numbers 112, 114, 116, 117, 118, 119, 120, 122, and 124, for which experimental data exist. These data have been obtained in the Sn(^{3}He,t)Sb charge-exchange reaction at the energy $E(^3\text{He})$ = 200 MeV. The comparison of calculations with experimental data on the energies of charge-exchange resonances gives the standard deviation $\delta E < 0.40$ MeV for microscopic numerical calculations and $\delta E < 0.55$ MeV for calculations by semi-classical formulas, which are comparable with experimental errors.
The same methods were used to calculate the resonance structure of other nuclei and the results of calculations showed good agreement with the experimental data. Of particular interest are the short-lived neutron-excess nuclei. The appearance of a pigmy resonance in the energy window of the beta-decay leads to a sharp decrease of the nucleus half-live. And when the pigmy resonance appears in the window of the beta-delayed neutron emission or beta-delayed fission, the corresponding probabilities increase strongly. This was recently observed in an experiment of studying the emission of delayed neutrons in highly neutron-rich calcium isotopes.
***(*Lutostansky, Tikhonov, 2016-2017). milestone 1a.**

Beta-decay rates and probabilities of beta-delayed processes

Beta-decay half-lives for the r-process nuclei and beta-delayed fission probabilities of transfermium nuclei, involved in the r-process, were calculated on the model approach based on the Finite Fermi-systems. The comparison with other predictions and exper-imental data was done. It was shown that the accuracy of beta-decay half-lives of short-lived neutron-rich nuclei is increasing with increasing neutron excess and can be used for modeling of nucleosynthesis of heavy nuclei in the r-process. For nuclei heavier than lead the half-lives of neutron-rich nuclei are on average 10 times smaller, than proposed of other predictions. (**Panov, Lutostansky, Thielemann, Nuclear Physics A, 947, 2016**).
For the nucleosynthesis of heavy and superheavy nuclei fission becomes very important when the r-process run in a very high neutron density environment. In part, fission is responsible for formation of heavy nuclei due to including fission products as new seed nuclei (fission cycling). More than that, beta-delayed fission along with spontaneous fission is responsible on the late stages of the r-process for the suppression of superheavy elements yields. The probabilities of beta-delayed fission and the beta-delayed neutron emission were calculated for transfermium neutron-rich nuclei, and the influence of beta-delayed fission upon superheavy elements formation was showen. (**Panov, Lutostansky, Thielemann. Journal of Physics: Conference Series, 665, 2016**). milestone 1b.

Alpha-decay energies, fission barriers and other characteristics of heavy nuclei

Fayans energy density functional (EDF) **FaNDF^0** has been applied to the heavy and super-heavy nuclei. Alpha-decay energies for several chains of super-heavy nuclei were calculated by using Fayans functional FaNDF0. They are compared to the experimental data and predictions of two Skyrme functionals, SLy4 and SkM*, and of the macro-micro method as well. The Fayans EDF results in the average deviation (rms) from experimental energies by $\langle\delta Q_\alpha\rangle_{tot}$ = 0.643 MeV with the surface pairing and 0.647 MeV with the volume pairing. These values are slightly larger than the corresponding SLy4 value of 0.593 MeV but significantly less than the SkM* value of 1.148 MeV. However, in this problem all the considered self-consistent methods give in the MMM the corresponding value being only 0.454 MeV.
The corresponding alpha-decay lifetimes were calculated with the use of the semi-phenomenological five-parameter formulas by Parkhomenko and Sobiczewski (PS), or, alternatively the twelve-parameter formulas by Royer and Zhang (RZ). It was shown, that the first method looks more accurate itself. The accuracy of all calculations with the use of theoretical Q_α values turns out a bit worse in the RZ case.
Neutron separation energies S_n, proton separation energies S_p, and the Q_β and β -transition energies were calculated for U, Np, and Pu isotopes. In addition, the deformation energies, deformation parameters and radii of these nuclei were considered. A comparison with predictions of the Skyrme–Hartree–Fock method for several versions of the Skyrme EDFs was made. Agreement with experiment for the function **FaNDF^0** in average of the same quality, as for the EF of the HFB family, which are recognized recorders in the accuracy of the nuclear masses description. SLy4 EDF is inferior in accuracy to both methods.

For the ^{238}U nucleus, the role of the octupole deformation β_3 is investigated. As it was shown, it does not practically influence the value $B(1)_f$ of the first fission barrier and the ground state characteristics as well. At the same time, the value $B(2)_f$ of the second fission barrier diminishes approximately twice after taking into account β_3. For three isotopic chains under consideration, some phase transition is observed at $A \approx 260$. A bifurcation occurs at this point, the $B(1)_f$ (A) curve splitting in two. Wherein the curve of $B(2)_f(A)$ is separated, which extends the previous one of $B(1)_f$ (A) almost continuously, whereas the curve $B(1)_f(A)$ itself sharply descends. (**see papers by Tolokonnikov et al., 2016, 2017***)*.

*(2) r-process modelling and nucleosynthesis (**Eichler, Panov, Thielemann, Nadyozhin, Kondratyev**)*

Nuclear data and r-process nucleosynthesis

We have performed r-process calculations in neutron star mergers (NSM) and jets of magneto-hydrodynamically driven (MHD) supernovae. In these very neutron-rich environments the fission model of heavy nuclei has an impact on the shape of the final abundance distribution and the second r-process peak in particular.
We have studied the effect of different fission fragment mass distribution models in calculations of low-Ye ejecta, ranging from a simple parametrization to extensive statistical treatments (ABLA07). The r-process path ends when it reaches an area in the nuclear chart where fission dominates over further neutron captures. The position of this point is determined by the fission barriers and the neutron separation energies of the nuclei involved. As both of these values depend on the choice of the nuclear mass model, so does the r-process path. The part of the nuclear data input for the r-process was also modified.

r-process in Supernova Neutrino Winds and the Influence of Magnetic Fields.

Neutrino forced r-process of the formation of neutron-rich nuclei in the explosion of SN in intensive neutrino flows with the capture of electron neutrinos by heavy elements has been simulated. This

process was taken into account in neutrino-induced r-process model, considered earlier (Nadyozhin, Panov , 2014).
It was shown that for considered model the speed-up of the r-process does not occur, contrary to our old model evaluations. It can be significant, but for smaller radii, where the temperature is rather high for the r-process.
Kondratyev considered magnetodynamics of inhomogeneous crusty nuclear matter accounting for quantum fluctuations and ferromagnetic coupling. It was shown that anomalies in nuclide magnetic moments give rise to erratic jumps in magnetotransport of neutron star crusts. Universal properties of such a noise are favorably compared with statistical and temporal features of Soft Gamma Repeating bursts. (**V. N. Kondratyev, et al. 29, 2016**). Nucleosynthesis at magnetorotational supernova explosion was considered by employing arguments of nuclear statistical equilibrium. Magic-antimagic switches in the nuclear shell structure in varying magnetic field lead to an increase of titanium binding energy and, consequently, to a noticeable increase of the portion of 44Ti in explosive nucleosynthesis products. Magnetic effects in nuclide creation are favorably compared to observational Integral data and galactic chemical composition. (**Kondratyev, &. Mishenina, 2016**), Explosive nucleosynthesis at conditions of magnetorotational instabilities is considered for iron group nuclides by employing arguments of nuclear statistical equilibrium. Effects of ultra-strong nuclear magnetization are demonstrated to enhance the portion of titanium product. The results are corroborated with an excess of 44Ti revealed from the Integral mission data. (**Kondratyev, 2016**). Soft repeating gamma-ray (SGR) bursts are considered as magnetoemission of crusts of magnetars (ultranamagnetized neutron stars). It is shown that all the SGR burst observations can be described and systematized within randomly jumping interacting moments model including quantum fluctuations and internuclear magnetic interaction in an inhomogeneous crusty nuclear matter. (**Kondratyev &. Korovina, 2016**). Effects of ultra-strong magnetization in creation of iron group nuclides are considered by employing arguments of nuclear statistical equilibrium. Nuclear magnetic reactivity is demonstrated to enhance the portion of titanium product due to magnetic modification of nuclear structure. The results are corroborated with an excess of 44Ti revealed from the Integral mission data (**Kondratyev, 2016).**

Comparison to Observations

Comparing observational abundance features with nucleosynthesis predictions of stellar evolution or explosion simulations, we can scrutinize two aspects: (a) the conditions in the astrophysical production site and (b) the quality of the nuclear physics input utilized. We test the abundance features of r-process nucleosynthesis calculations for the dynamical ejecta of neutron star merger simulations based on three different nuclear mass models: The Finite Range Droplet Model, the (quenched version of the) Extended Thomas Fermi Model with Strutinsky Integral, and the Hartree–Fock–Bogoliubov mass model. We make use of corresponding fission barrier heights and compare the impact of four different fission fragment distribution models on the final r-process abundance distribution. Utilizing sophisticated fission fragment distribution leads to a highly improved abundance distribution.

We explore the abundance distribution in the second r-process peak and the rare-earth sub-peak as a function of mass models and fission fragment distributions, as well as the origin of a shift in the third r-process peak position. The latter has been noticed in a number of merger nucleosynthesis predictions.
There were shown that the shift occurs during the r-process freeze-out when neutron captures and β-decays compete and an (n,γ)–(γ,n) equilibrium is no longer maintained. During this phase neutrons originate mainly from fission of material above A = 240. The role of β-decay half-lives from recent theoretical advances was also investigated. The chosen rates lead to a smaller amount of fissioning nuclei during freeze-out or a faster (and thus earlier) release of fission neutrons, which can (partially) prevent this shift and has an impact on the second and rare-earth peak as well. **(Eichler, M., et al. Journal of Physics: Conference Series, 665, 2016).**

(3) The Age of the Universe ***(Eichler, Lutostansky, Panov, Thielemann)***

In the present project, we addressed the question of how the values that ratios of the abundances of uranium and thorium isotopes may assume for various scenarios of the r-process depend on the character of the nucleosynthesis — that is, on model parameters and non-steady-state conditions of nucleosynthesis that are determined by the change in the conditions of galactic nucleosynthesis (from an instantaneous to a uniform process) and on the implications of the supernova explosion before the formation of the solar system.

The effect of a nucleosynthesis spike before the formation of the solar system was analyzed and the consistency of the cosmochronometric-ratio values calculated for various specific scenarios of the r-process and within various galactic-nucleosynthesis models was examined. A direct solution of three differential equations (involving an additional pair, 244Pu/238U) with the aim of determining the age in question on the basis of a specific model was found.

On the basis of analysis for compatibility of the models, scenarios, and nuclear data used we have shown that the abundance ratios 235U/238U and 232Th/238U have to be less than unity – in accordance with recent predictions [Eichler et al., 20016] for the abundances of cosmochronometer nuclei – to describe the Universe age in the limits of Tg~13-15 billion years.

Also, according with project plan, 4 nuclear cosmochronometers for definition of Universe age were considered . The additional pair of cosmochronometer nuclei, 244Pu and 238U, was added to the model. The inclusion of the 244Pu/238U calculated ratio of their abundances, $\lambda 48$, made it possible to find the age of the Milky Way Galaxy via directly solving the set of equations.

The values obtained in this way for TG fall within the range (in billion yr units) of $11.0 < Tg < 13$ for the strength of a nucleosynthesis spike in the range of $S < 0.01$; are close to present observational data and suggest, first, the presence of a nucleosynthesis spike and, second, an exponential nucleosynthesis type close to a uniform one. In any case, it is most likely that only within models involving a nucleosynthesis spike before the formation of the solar system the calculations of the age of the Milky Way Galaxy can be matched with the region of admissible values for the ratios of the abundances of cosmochronometer nuclei. The method of the region of admissible values can be used to test the consistency of scenarios of the r-process and nuclear data. (**Panov et al. 2017). milestones 3**.

III. Abundance determination and chemical evolution of galaxies

*(1) Improved stellar abundances of neutron-capture elements (**Mashonkina, Sitnova, Mishenina, Gorbaneva, North, Jablonka**)*

Sr, Ba, Eu

Despite many theoretical and observational studies of the neutron-capture elements in the long-lived stars in our Galaxy, there are not yet clear answers to the questions what is (are) astrophysical site(s) of the rapid (r) process of neutron-capture nuclear reactions, what types of nuclear reactions produced the light trans-iron elements, Sr-Zr, in the early Universe and at what astrophysical site(s), whether or not the light and heavy (beyond Ba) elements originate from a common astrophysical site.

Mashonkina&Sitnova determined the non-LTE (NLTE) and LTE abundances of Sr, Ba, and Eu in a sample of 23 very metal-poor (VMP, [Fe/H] < -2) halo giants based on a homogeneous set of atmospheric parameters and high-resolution observed spectra. The [Sr/Fe] and [Ba/Fe] abundance ratios have large dispersion below [Fe/H] ≈ -2.8, independent of either LTE or NLTE. Above this metallicity, [Sr/Fe] becomes steadily solar. As to [Ba/Fe], the rise to the solar value comes at slightly higher metallicity, [Fe/H] ≈ -2.5. Although largely diminished, the dispersion is larger than for [Sr/Fe]. These results are in line with the earlier studies of VMP giants (for example, Honda et al. 2004, ApJ, 607, 474; Andrievsky et al. 2011, A&A, 530, A105) and also VMP dwarfs, as determined by Zhao et al. (2016, ApJ, 833, 225). The Eu abundance could only be measured for 8 sample stars. The [Eu/Fe] ratios reveal large scatter of data below [Fe/H] ≈ -2.2 and lie close to the VMP dwarfs above this metallicity. Whether large dispersion of Sr/Fe, Ba/Fe, and Eu/Fe at low metallicities was caused by unwell mixing of the interstellar medium or a contamination from the dwarf spheroidal galaxies orbiting the Milky Way need further investigations. The ratios among the neutron-capture elements form well-defined abundance trends. The Eu/Ba abundance ratios suggest the r-process production of Ba and Eu. Indeed, [Eu/Ba] ranges between 0.28 and 1.12 and is much closer the r-process [Eu/Ba]r = 0.80 (based on the solar r-residuals, Bisterzo et al. 2014, ApJ, 787, 10) than the s-process [Eu/Ba]s = 1.15 ratio. Would Ba and Sr be produced by the same nucleosynthesis source, this should result in a fairly flat [Sr/Ba] ratio versus [Ba/H]. This is clearly not the case in the investigated stellar sample that forms two branches for Sr/Ba, suggesting two different nucleosynthesis channels for Sr. Eight of 20 stars have indeed similar [Sr/Ba] ~ -0.5 on the entire range of Ba abundances. Although astrophysical site(s) of the r-process is (are) not identified yet, the strongly r-process enhanced ([Eu/Fe] > 1, [Eu/Ba] > 0) stars referred to as r-II stars provide an observational evidence for a subsolar Sr/Ba ratio in the r-process synthesis. The r-process ratio, [Sr/Ba]r = -0.38, was estimated empirically using the Sr and Ba abundances from the literature for six r-II stars. When the observed subsolar Sr/Ba ratio serves as a signature of the r-process origin of Sr, one can conclude that not only Ba, but also Sr in our eight halo stars originate from the r-process. The second MW group seems to be aligned on a well-defined upward trend of [Sr/Ba] with decreasing [Ba/H]. It is worth noting that the [Ba/H] ≤ -2 dwarfs from Zhao et al. (2016) lie close to this trend. Similar tight anti-correlation of [Sr/Ba] with [Ba/Fe] and [Ba/H] was reported by Honda et al. (2004) and Francois et al. (2007, A&A, 476, 935). In order to explain an excess of Sr production relative to the classical r-process, various ideas and models were proposed in the literature, however, the source(s) is (are) not identified yet. Accurate and homogeneous data on Sr, Ba, and Eu abundances in a sample of VMP giants and dwarfs obtained in this project can serve future nucleosynthesis models.(**Mashonkina, Jablonka, North, Sitnova, 2016**, Proceedings of the IAU, IAUS317, p. 334-335**)..** major contribution for **milestones, such as 5 and 7a.**

Mashonkina measured both the Ba II 4554 Å resonance line, which has a notable hyper-fine splitting (HFS) structure, and the Ba II 5853, 6496 Å subordinate lines, which are nearly free of the HFS effect, **i**n 13 stars of that same giant sample. For every star, the abundance obtained from the resonance line is higher than that from the subordinate lines, when assuming a solar fraction of the Ba odd-A isotopes of f_{odd} = 0.18. Exception is HD 122563, for which f_{odd} = 0.18 leads to consistent abundances from different Ba II lines, in line with the earlier determination of f_{odd} = 0.22±0.15 (Mashonkina et al. 2008, A&A, 478, 529). Applying the r-process fodd = 0.46 (Travaglio et al. 1999, ApJ, 521, 691) largely removes the abundance difference between the Ba II resonance and subordinate lines. Thus, one can conclude that the barium even-A and odd-A isotopes in the 12 investigated halo stars were produced in equal amounts and this serves to constrain the r-process models (**work in progress**, major contributions to a number of **milestones, such as 4, 5, 7a.**

Gorbaneva & Mishenina used the calculations of the Galactic enrichment by Travaglio et al. (2004) and Serminato et al. (2009) to provide diagnostics of the types of n-capture processes forming Sr, they. Both models take into account the contribution from the main s-process in the asymptotic giant branch (AGB) stars, the weak s-process component and the r-process in Type II supernovae (SNeII) stars. The primary process (or LEPP) is also taken into account in model of Travaglio et al. (2004). Serminato et al. (2009) used first the r-process residual method (r = 1 - s) and then the r-contribution from SNeII. Both models describe quite well a behavior of the thin disk stars, albeit in some different ways. Note, the models which consider the contribution only from the s-process do not depict well the observation. (**Gorbaneva, Mishenina,** OAP, v. 29, 2016).. major contribution to **milestone 5.**

(2) *NLTE effects on abundance determinations and constraints to chemical evolution models (**Sitnova, Mishenina, Andrievsky, Gorbaneva, Korotin Koytyukh**)*

Alpha-elements O, Ti

Sitnova determined the titanium and oxygen NLTE and LTE abundances for a sample of nearby FGK dwarf stars, with well-known atmospheric parameters and an iron abundance in the -2.6 < [Fe/H] < 0.2 range. The [O/Fe] and [Ti/Fe] abundance ratios form well-defined Galactic trends, with much smaller scatter of data for the stars of close metallicities compared with the published data. It was established that [O/Fe] increases from -0.2 to 0.6 as [Fe/H] decreases from 0.2 to -0.8 and remains constant at a lower metallicity. A similar behavior was found for [Ti/Fe], but the plateau is formed at [Ti/Fe] = 0.3. These results confirm that not only oxygen but also titanium are synthesized in the alpha-process. These data can be used to test the Galactic chemical evolution models. (**Sitnova, Astronomy Letters, v. 42, 2016; Sitnova et al., MNRAS, 461, 2016**).. major contribution to a number **of milestones, such as 4, 5, 7a**

O, Ti, V, Sc, Cr, Fe, Mn

Mishenina, Pignatari, Thielemann, Gorbaneva, Korotin, Kovtyukh determined with high precision atmospheric parameters and chemical composition for ten stars with metallicity in the region −2.2 < [Fe/H] < −0.6, using spectra obtained with the 1.93-m / SOPHIE echelle spectrograph. For each star, the LTE and NLTE abundances were derived for 7 to 19 elements. The O abundance has the largest error, ranging between 0.10 and 0.2 dex. The best measured elements are Cr, Fe and Mn, with the errors between 0.03 and 0.11 dex. These new results were compared with stellar observations from different data sets and a number of theoretical galactical chemical evolution simulations. It was confirmed that the chemical evolution of the elemental ratios [Sc/Fe], [Ti/Fe] and [V/Fe] is not reproduced at different metallicities by any of the GCE models. The stellar yields from core collapse supernovae (CCSN) is the main source of this discrepancy, which is one of the most important puzzle that modern multi-dimensional CCSN simulations need to solve (**MNRAS 469, 2017**).. major contribution to a number of **milestones, such as 5 and 7a**

S, Zn

Andrievsky & Korotin took part in the study of S and Zn in a large number of Galactic stars. Due to their volatile nature, when S and Zn are observed in external galaxies, their abundances represent the gas-phase abundances in the interstellar medium. This implies that they can be used as tracers of the chemical enrichment of matter in the Universe at high redshift. Comparable observations in stars are more difficult and, until recently, plagued by small number statistics. Duffau et al. exploited the Gaia ESO Survey (GES) data to study the behaviour of S and Zn abundances of a large number of Galactic stars, in a homogeneous way. By using the UVES spectra of the GES sample, a sample of 1301 Galactic stars was assembles, including stars in open and globular clusters in which both sulfur and zinc were measured. It was confirmed that sulfur behaves as an alpha-element. A large scatter of [Zn/Fe] ratios was found for giant stars around solar metallicity. The lower ratios are observed in giant stars at Galactocentric distances less than 7.5 kpc. No such effect is observed among dwarf stars, since they do not extend to that radius. Given the sample selection, giants and dwarfs are observed at different Galactic locations, and it is plausible, and compatible with simple calculations, that Zn-poor giants trace a younger population more polluted by SN Ia yields. It is necessary to extend observations in order to observe both giants and dwarfs at the same Galactic location. Further theoretical work on the evolution of zinc is also necessary (**accepted by A&A)**... major contribution to a number of **milestones, such as 5 and 7a**

Fe, Mg, Si, Ca, Ti

Andrievsky, Kovtyukh, Korotin derived abundances of 36 chemical elements in a Cepheid star ASAS 181024-2049.6 located at RG = 2.53 kpc from the Galactic Centre. This star falls within a region of the inner thin disc poorly sampled in Cepheids. It was shown that the iron, magnesium, silicon, calcium, and titanium LTE abundances of that star support the presence of a plateau-like abundance distribution in the thin disc within 5 kpc of the Galactic Centre, as previously suggested by Martin et al. If confirmed, the flattening of the abundance gradient within that region could be the result of a decrease in the star formation rate due to dynamic effects. (**Andrievsky,et al. MNRAS 461, 2016**)..).. major contribution to **milestone 5**

(3) *Improved stellar chemical abundances (**Mishenina, Koytyukh, Chekhon-adskikh, Usenko, Yushchenko,Andrievsky, Korotin**)*

A general overview from Li to Eu

Mishenina & Kovtyukh analysed the distribution of elements from Li to Eu in 200 dwarfs in the solar neighbourhood (~20 pc) with T_{eff} = 4800-6200 K and [Fe/H] > -0.5. Stellar atmospheric parameters and chemical compositions were taken from the previous studies. It was found that the lithium abundances of the planet-hosting solar-analogue stars are lower than for the stars without planetary systems. The obtained results reveal no significant differences for the investigated elements, except for aluminium and barium, which are more and less abundant in the planet-hosting stars, respectively. No confident dependence of the lithium, aluminium and barium abundances on the stellar age was found that is probably because of the small statistics. No correlation was found between the [El/Fe] differences and the condensation temperature (Tcond) for the 16 Cyg binary system, unlike 51 Peg, for which a slight excess of volatile elements and a deficit of refractories were obtained relative to those of solar twins. One of the components of 16 Cyg exhibits a slightly higher average abundances than its counterpart: <[El/H](A - B)> = 0.08 ±0.02 dex; however, no significant abundance trend versus Tcond was observed (**MNRAS 462, 2016**).. major contribution to **milestone 5**

Alpha, Fe-peak, n-capture elements

Kovtyukh & Chekhonadskikh determined detailed chemical abundances (α, iron-peak and neutron-capture elements) for an almost complete (18/24) sample of Galactic double mode Cepheids (also called beat Cepheids) and calibrated a new relation between their metallicity and their period ratio P1/P0. This linear relation allows to determine the metallicity of bimodal Cepheids with an accuracy of 0.03 dex in the [Fe/H] = +0.2 to -0.5 dex range. Extrapolating the relation to Magellanic Clouds beat Cepheids provides their metallicity distribution function. Using this relation also provides the first metallicity estimate for the two double-mode F/1O Cepheids located in and beyond the Galactic bulge. A super-Lithium rich double mode Cepheid V371 Per was discovered, with logA(Li) = 3.54±0.09 dex. Along with V1033 Cyg (an ordinary classical Cepheid), it is the second known Cepheid of such type in the Galaxy **(MNRAS 460, 2016)**).. major contribution to **milestone 5**

C, N, O, Na, Mg, Al

Usenko performed spectroscopic study of the classical Cepheid ζ Gem based on five high-resolution spectra that cover the ascending branch of the light curve from minimum to maximum. Atmospheric parameters and chemical composition of ζ Gem were refined: [Fe/H] = +0.01 and the remaining abundances are nearly solar. The abundances of the key elements were found to be typical for an object that has passed the first dredge-up: C underabundance, N, Na, and Al overabundances, and nearly solar O and Mg abundances. The metal absorption lines show a clear asymmetry and the formation of secondary blue (B1 and B2) and red (R1 and R2) components. The Hα absorption line is also split into blue (B) and red (R) components with depths changing with pulsation phase. The radial velocity estimates for the metal lines and their B1 and B2 components are found to depend on the line depths, suggesting the presence of a velocity gradient in the atmosphere. The mean velocity estimate for the R component of the Hα line at all phases is +32.72 ± 2.50 km s-1 and differs significantly from the others, suggesting the formation of this component in the envelope around the Cepheid (**Usenko I.A. Astron. Letters 42, 2016)** .. major contribution to **milestone 5**

Usenko obtained high-resolution spectra of nine yellow non-variable supergiants located within the canonical Cepheid instability strip. Abundances of the alpha-elements and the r- and s-process elements were found to be close to the solar ones. Estimates of the CNO, Na, Mg, and Al abundances show that eight of the nine stars already passed the first dredge-up. Judging by the abundances of the key elements and its position on the H-R diagram, the Li-rich supergiant HD 172365 is at the post-main-sequence evolutionary stage of gravitational helium core contraction and moves toward the first crossing of the Cepheid instability strip. ε Leo should be assigned to bright giants, while HD 187299 and HD 190113 may have already passed the second dredge-up and move to the asymptotic giant branch (**Usenko I.A. Astron Letters 43, 2017)** .. major contribution to **milestone 5**

Large abundance surveys: up to 35 elements, including Tl, U

Yushchenko V. took part in a study of the eclipsing binary system RR Lyn based on high-resolution spectral observations with the 1.8 m telescope at the Bohuynsan Optical Astronomical Observatory in Korea. Jeong et al. found effective temperatures (T_{eff} = 7920 and 7210 K), surface gravities (log g = 3.80 and 4.16), and abundances of 34 and 17 chemical elements for the primary and secondary components, respectively. Correlations of the derived abundances with the condensation temperatures and the second ionization potentials of these elements are discussed. The primary component is a typical metallic line star with the abundances of light and iron-group elements close to solar values, while elements with Z > 30 are overabundant with respect to solar values, by 0.5-1.5 dex. The secondary component is a λ Boo type star. In this type of stars, CNO abundances are close to solar values, while the abundance pattern shows a negative correlation with the condensation temperatures **(J. Astron. Space Sci. 34(2), 2017)** .. major contribution to **milestone 5**

Yushchenko V. investigated a red supergiant PMMR23 located in the region of Small Magellanic Cloud with low velocities of stars and interstellar gas. Abundances of 35 chemical elements and the upper limits for Tl and U were found. Abundances of the heavy elements are enhanced with respect to iron-group elements, by 0.6-1.0 dex. Spectra of the SMC red supergiants PMMR27, PMMR48, PMMR102, and PMMR144 located in the region of high velocities of stars and interstellar gas show the emission components in the Halpha wings. Such an emission is not detected for PMMR23. This study used the spectra obtained at ESO 3.6 meter telescope with R = 30000. Yushchenko A. et al. discuss a possibility of accretion of interstellar gas on the atmospheres of PMMR23 and other supergiants in Magellanic Clouds. (**accepted** to Kinematika Fizika Nebesnyh Tel (**Kinematics and Physics of Celestial Bodies**, v. 33, № 5). .. major contribution to **milestone 5**

Li

Mishenina analyzed the connection of superflares and the Li abundance in the 280 G and K stars based on the Li abundance determinations. It was found that the samples of stars with high Li abundance and having superflares possess common properties. This relates, first of all, to the stars with activity saturation. Katsova et al. consider the X-ray data for G, K, and M stars separately and show that the transition from a saturation mode to solar-type activity takes place at values of rotation periods of 1.1, 3.3, and 7.2 days for G2, K4 and M3 spectral types, respectively. They discuss a bimodal distribution of a number of G and K main-sequence stars versus an axial rotation and location of superflare stars with respect to the Kepler stars. They conclude that the superflare G and K stars are mainly fast-rotating young objects, but some of them belong to the stars with solar-type activity. They found a group of G stars with high Li abundance (log A(Li) = 1.5 - 3), but being slower rotators (rotation periods > 10 days). This agrees with a large spread in Li abundances in the superflare stars (**Katsova, et al., 2016)** .. major contribution to **milestone 5**

Equivalent Widths and Reddening for Cepheids

Andrievsky, Chekhonadskikh, Kovtyukh, Korotin investigated the diffuse interstellar band (DIB) at 661.3 nm seen in the spectra of Cepheid stars. After removal of the blending lines of Y II and Fe I, they determined the equivalent widths (EWs) of the DIB and used these values to investigate the E(B-V) – EW(DIB) relation. The relation found from Cepheids matches that found in B stars. It can help to find the reddening for newly discovered Cepheids without extensive photometric data and thus to determine their distances. The relation E(B-V) – EW(DIB) does not yield precise reddening values. At best, it is indicative, but it provides some information that may not be otherwise available. Defining R* = E(B-V)/EW(DIB), which is considered as the analogue of R = E(B-V)/Av, we investigated the Galactic longitudinal dependence of R* assuming that EW(DIB) is representative of the interstellar absorption Av. It was found that there is an apparent increase of the R* value that corresponds to the abnormal absorption seen towards Cygnus constellation. Finally, they constructed a 2D map of the EW(DIB) distribution in the Galactic disc based on a rather limited sample of 253 spectra of 176 Cepheids (**Kashuba, S. V., et al., MNRAS 461, 2016)**.. **beyond the project program**

Highlights of the Collaboration:

In previous years we planned that in alternating years the Russian/Ukrainian members *either* visit their western counterparts and attend workshops/conferences in the West *or* organize joint workshops in Russia or the Ukraine. In the spring and summer of 2015 a number of our collaborators (from the Odessa group led by T. Mishenina) participated in the “Nuclear Physics in Astrophysics” Conference in York (UK) and in spring of 2016 in the “Nuclear Astrophysics” workshop (from the Moscow group, led by S. Blinnikov) at the Ringberg Castle (Tegernsee, Germany). In both conferences also members of the Geneva team (led by G. Meynet) participated. In principle, in 2016 we would have again planned a joint workshop either in Moscow or Odessa. Given the political situation in the Ukraine, and realizing that there will be no realistic chance to have a joint meeting either in Russia or the Ukraine for all eastern participants in 2016, we also invited our eastern collaborators to the biannual Basel get-together “Brainstorming and Fun” for the fall of 2016 with participation of almost all of our Russian/Ukrainian collaborators. For the same reasons this had been already organized in the same way in fall 2014, when we had a very strong feedback from our Eastern colleagues how much they enjoyed the scientific atmosphere, giving a much broader background (and feedback on their talks) than an only SCOPES meeting. In addition, we had mutual get-togethers at a number of international scientific meetings listed below, extended visits of I. Panov in Basel (2015, 2016, and 2017), and a final get-together in Moscow in July 2017 (unfortunately without our Ukrainian colleagues in person, but with skype connection).

This overall environment led to quite successful joint collaborations and projects and to major publications on the main topics of our joint proposal: nuclear physics input to nucleosynthesis (Moscow-Basel), nucleosynthesis ejecta from rotating massive stars (Geneva-Basel), the formation of the heaviest nuclei in a rare class of supernovae as well as neutron-star mergers (Basel-Moscow), the contribution of type Ia supernovae (Odessa-Basel), and galactic chemical evolution (Odessa, Geneva, Basel, Moscow). The joint publications listed in the bibliography give a clear indication that this was very successful and is actually ongoing after the end of this grant. The publications and the presentations at international conferences provide a strong proof for the international recognition and scientific quality of the research performed by all partners.

While we mentioned major conferences where all partners could participate and meet, we list here also the conference and workshops that could be attended by the Odessa and/or Moscow groups. The talks and reports presented there are listed at the end of the bibliography:

- *Nuclear Physics in Astrophysics VII, 28th EPS Nuclear Physics Divisional Conference, York (United Kingdom) 18 May - 22 May 2015*

- Int. Conference on Nuclear Physics «NUCLEUS 2015». New horizons in nuclear physics, nuclear engineering, femto– and nanotechnologies (LXV meeting on nuclear spectroscopy and nuclear structure). June 29 – July 3, 2015 Saint-Petersburg, Russia.

- 5th Gamow International Conference "Astrophysics and Cosmology after Gamow: progress and perspectives", 16-23 August, 2015, Odessa, Ukraine

- Int. Conference "High Energy Astrophysics", 21-24 December 2015, Moscow, Russia

- *European Week of Astronomy and Space Science, La Laguna, Tenerife, Canary Islands, Spain, 22-26 June 2015*

- International conference - XVII Khariton's topical scientific readings "Extreme states of matter: Detonations, Shock waves", March 23 – 27, 2015. Sarov, Russia

- International conference "Frontiers of Stellar Spectroscopy in the Local Group and beyond", April 27-30, 2015, Heidelberg, Germany

- *IAU Symposium 317 "The General Assembly of Galaxy Halos: Structure, Origin and Evolution", during the IAU GA XXVIII, August 3-10, 2015, Honolulu, USA*

- International conference "Radiation mechanisms of astrophysical objects: classics today", September 21-25, 2015, St. Petersburg, Russia

- International Conference on Nuclear Structure and Related Topics (NSRT15), Dubna, Russia, July 14-18, 2015

- "All-Wavelength Astronomy: Shklovsky100", 20-22 June, 2016, Moscow, Russia

- *"First stars V", 1-5 August 2016, Heidelberg, Germany*

- *18th Workshop on Nuclear Astrophysics, Ringberg Castle, Germany, March 14-19, 2016*

- "Dark Ages and White Nights", Saint-Petersburg, Russia, June 20-24 2016

- "Non-ideal plasma physics", Presidium RAS, Moscow, Russia, 7-8 December 2016

- VIII International Symposium on Exotic Nuclei, Kazan, Russia, 5 - 10 September 2016

- "Stars: from collapse to collapse", 3-7 October 2016, Special Astrophysical Observatory, Russia

- Int. Conf. on nuclear spectroscopy and nuclear structure, 11-14 October 2016, Sarov, Russia

- *EWASS 2016, 6 – 8 July 2016, Athens, Greece*

- "High Energy Astrophysics Today and Tomorrow", 20-23 December 2016, Moscow, Russia

- 19th Cambridge Workshop on Cool Stars, Stellar Systems, and the Sun (CS19), Uppsala, Sweden, 6-10 June 2016

- "Solar and Solar-Terrestrial Physics - 2016", St. Petersburg, Pulkovo, Russia, 10 - 14 October

- "Stars on the run", a meeting on runaway and hyper-velocity stars, Germany, Bamberg, August 16-19, 2016

- VIII Scientific Conference "Selected issues of astronomy and astrophysics" in honor of Babiy (1936-1993) Lviv-2016, 17-20 Oct, 2016

- International Meeting on Variable Stars Research "KOLOS-2016", 2016 December 1-3, Stakcin, Slovakia, 3

- **Brainstorming and Fun 2016 "Compact objects, their equation of state, related explosive events, and their nucleosynthesis", Basel, Switzerland, 29 Sept. - 1 Oct. 2016 (Joint Scopes Meeting)**

- "Physics of stars from collapsing to collapse", SAO RAN, Nizhniy Arkhyz, 3-7 October 2016

- 16th Odessa International Astronomical Gamow Conference-School "Astronomy and beyond: Astrophysics, Cosmology and Gravitation, Cosmomicrophysics, Radio-astronomy and Astrobiology", Ukraine, Odessa, Chernomorka, 14-20 August, 2016

- *"The Galactic Renaissance", 1-3 February 2017, Caltech, USA*

- "30 years of SN 1987A", 2-3 March 2017, Moscow, Russia

- "Physics of Neutron Stars", 10-14 July 2017, Saint Petersburg, Russia

- 14. Int. Conf. "Physics of Neutron Stars – 50 years after", July 10 - 14, 2017, Saint Petersburg, Russia

- *"The Progenitor-Supernova-Remnant Connection", July 24 - 28, 2017, Ringberg Castle, Germany*

- “30th Anniversary of SN 1987A”, Moscow, Russia, 2-3 March 2017, Moscow, Russia

- “Physics of fundamental interactions" dedicated to 50th anniversary of Baksan Neutrino Observatory. 6-8 June 2017, Nalchik, Russia

- “SN 1987A, Quark Phase Transition in Compact Objects and Multimessenger Astronomy", 2-8 July 2017, KBR, Terskol (BNO); KChR, Nizhnij Arkhyz (SAO), Russia

- *IAU Symposium 330 “Astrometry and Astrophysics in the GAIA Sky”, Nice, France, 24 - 28 April 2017*

- *“European Week of Astronomy and Space Science 2017, 26 – 30 June 2017, Prague, Czech Republic*

- “Astrocamp VARIABLE 2017”, Astronomical Observatory on Kolonica Saddle, Slovakia, 17 - 26 July, 2017

- **“Galactic chemical evolution and heavy elements nucleosynthesis”, 3-4 July 2017, Moscow, Russia (Joint Scopes Meeting)**

- *“Stellar Evolution, Supernovae, and Nucleosynthesis across Cosmic Times”, 18-30 September 2017, Tokyo, Japan*

2.2 Is the co-operation progressing satisfactorily according to expectations with regard to collaboration?

As seen from the details given above, all groups were very active in their related and overlapping research fields from nuclear input over stellar modeling and abundance observations in stars, to their interpretation in the chemical evolution of galaxies. Also a number of joint investigations of at least two of the participating groups took place and are still ongoing.
The direct face-to-face meeting at 13 workshops/conferences (for members of more than two participating groups, including members of the Swiss groups) and 2 general meetings of the joint collaboration has increased the overlap and joint planning strongly. In the list of publications given at the end of the report, one can recognize that a true collaboration has developed. There are in total **29 joint publications (boldface)**, which include members of more than one of the participating research groups. One also finds in total 31 publications of our Eastern European Partners with collaborators from the West (underlined), emphasizing that our partners have an international standing, going beyond the collaboration with the Swiss groups.

2.3 Please list the involved individuals: (with their age at the end of the project)

2.3 Please list the involved individuals.

Name	Country	Age	Sex	Remarks
Andrievsky Sergei	Ukraine	56	M	Prof
Chekhonadskhih Fedor	Ukraine	32	M	Scientist
Korotin Sergei	Ukraine	55	M	senior scientist
Mishenina Tamara	Ukraine	67	F	Prof
Yushchenko Volodymyr	Ukraine	31	M	PhD student

Kondratyev Vladimir	Ukraine	57	M	scientist
Baklanov Petr	Russia	39	M	engineer
Blinnikov Sergey	Russia	70	M	Prof
Glazyrin Semen	Russia	31	M	Postdoc
Mashonkina Lyudmila	Russia	66	F	Prof
Lutostansky Yuriy	Russia	72	M	Prof
Panov Igor	Russia	66	M	Prof.
Potashov Marat	Russia	35	M	PhD student
Sitnova Tatiana	Russia	28	F	PhD student
Yudin Andrey	Russia	39	M	scientist
Corinne Charbonnel	Switzerland	52	F	Prof
Athur Choplin	Switzerland	31	M	PhD student
William Chantereau	Switzerland	31	M	PhD student
Georges Meynet	Switzerland	59	M	Prof
Sylvia Eckström	Switzerland	51	F	scientist
Patrick Eggenberger	Switzerland	37	M	scientist
Friedrich-K. Thielemann	Switzerland	66	M	Prof.
Matthias Liebendörfer	Switzerland	52	M	Lecturer
Thomas Rauscher	Switzerland	52	M	Lecturer
Marco Pignatari	Switzerland	39	M	Ambizione Fellow
Matthias Hempel	Switzerland	36	M	Postdoc
Ruben Cabezon	Switzerland	40	M	Postdoc
Kuo-Chuan Pan	Switzerland	36	M	Postdoc
Marius Eichler	Switzerland	30	M	PhD student
Kevin Ebinger	Switzerland	30	M	PhD student
Julia Reichert	Switzerland	31	F	PhD student
Maik Frensel	Switzerland	31	M	PhD student
Benjamin Wehmeyer	Switzerland	29	M	PhD student
Oliver Heinimann	Switzerland	29	M	PhD student

3. Practical issues

3.1 Did you encounter any major problems (e.g. telecommunication, transfer of goods, taxation, customs)? If yes, please specify the problems and describe how you solved them.

The new laws in Russia, discriminating any connection which receives money from outside the country as a foreign agent, makes money transfers almost impossible by now. The last transfers to the group in Moscow were provided via cash during visits in Basel.

3.2 How did you transfer the funds to the project partners in Eastern Europe?

Since 2011 (i.e. during the previous Scopes grant) the Russian team had used an individual CHF-account at UBS in Basel. For more transparency in the financial report the Russian team leader opened an additional sub-account at UBS only for SNF-transfers and payment of individual grants. As in previous years, the budget was sent, according to the rules of the SNF (Guidelines for the Administration of Grants for Joint Research Projects, item 4.), in 2 annual installments until early 2016. This was changed for the last transfers (see 3.1).
The Ukrainian team leader used a CHF-account at UKRSIBBANK in Odessa for the transfers from SNF. The money was sent, according to the rules of the SNF (Guidelines for the Administration of Grants for Joint Research Projects, item 4.), in 1 annual installment.

3.3 Are there important developments/changes in the scientific landscape of the involved partner countries?

The evolving situation in the Eastern part of Ukraine with strong Russian involvement did not help the overall political climate between the two countries that are both partners in this SCOPES project. Fortunately, this did not have an effect on our science or the involved individuals. But it required to suspend the planned 2015 joint meeting in Odessa, which would have fitted perfectly into the 5th Gamow International Conference and it did not permit the Ukrainian partners to participate in the final joint meeting in Moscow in July 2017.

4. Annexes

Include any documents (publications, proceedings, etc.) which you consider to be of relevance.

Bibliography

4.1 Publications in Journals

This section serves as bibliography, listing articles published and prepared by the SCOPES partners during the full grant period. This listing serves essentially to show the activities by the SCOPES partners from Moscow and Odessa (given in italic), and ***in bold fonts joint publications involving several SCOPES partners.*** *<u>To show the international standing of our Eastern partners, we also list their joint publications with other international groups (West or Asia) in an underlined way</u>. Individual publications by the Basel and/or Geneva groups are given in their individual SNF reports, but are not shown here, and* ***the OUTPUT DATA on the SNF website only list the joint publications****.*
The listing below shows that all partners continued individual work in their respective fields of expertise, but made joint efforts in overlapping areas, i.e. in nuclear decay rates, in stellar evolution, in stellar explosions related to the formation of heavy and the heaviest elements, and in understanding the chemical evolution of galaxies.

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