SCIENTIFIC REPORT

International Symposium „*The Modern Physics of Compact Stars*“
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1. Summary

The meeting took place in Yerevan within the envisioned time interval and within the scientific framework outlined in the proposal. The opening and closing sessions were held at the Department of Physics of Yerevan State University, while the remainder sessions took place at the conference hall of the Golden Palace hotel. Both locations offered best conditions for carrying out an international science meeting. The participants were offered a number of cultural events, including those that were related to the celebrations of the 100th birthday of the world-known astrophysicist Academician Victor A. Ambartsumyan.

The topics that were covered by the talks can be roughly divided into four subfields: (i) compact stars as sources of gravitational waves; (ii) physics of dense matter, including the nuclear and subnuclear (quark) phases; (iii) superfluidity and vortex state in compact stars; (iv) outer layers and the magnetosphere of a neutron star.

In the first subfield, one should highlight the recent progress made in simulations of binary neutron star inspiral (L. Rezzolla), which are the most promising sources of gravitational waves and offer a viable mechanism of gamma ray bursts. Furthermore, progress has been made in simulating magneto-rotational collapse of neutron stars (S. Moiseenko) and in treatment of the general relativistic oscillations of rapidly rotating neutron stars (E. Gaertig). The future development of this subfield depends on such factors as the available input from the micro-physics of matter (equation of state and neutrino interactions) as well as more analytical understanding of macro-physical phenomenal such as various instabilities. At the microphysical front there has been an interesting discussion on nuclear physics aspects of neutron stars. M. Sargsian presented and interpreted the recent results form the JLAB experiments which indicate that there are strong proton-neutron correlations in nuclei at short distances. Extarpolations to neutron star matter suggest that their cooling and equation of state will be affect by the broadening of the proton spectral functions. Other issues that were covered included the physics of neutron star crust (J.

Margueron), formation of clusters in dilute nuclear matter (G. Roepke), the role of three-body forces for neutron star stability (H. Schulze), and recent Monte-Carlo simulations of nuclear systems (S. Illarinov). Very interesting recent results were presented in the third subfield of superfluidity and vortex state in neutron stars, in particular the simulations of the vortex dynamics with a stack of pinning centers (B. Link), transition from type-I to type-II superconductivity in superfluid mixtures (M. Alford) and vortex shear modes and their implications for neutron stellar oscillations (A. Sedrakian). In the fourth subfield illuminating discussion was devoted to the physics of photon propagation in the outer layers of neutron stars, transport coefficients in strongly magnetized plasma and resonant conversion of photos, etc (D. Lai). The scientists from the Faculty of Physics of Yerevan State University engaged in the conference by presenting in total 9 talks on the subject of the conference and by actively contributing to the discussions.

To summarize, the conference offered a unique opportunity to bring together experts working on different aspects of neutron stars. The main impact of the symposium was the first hand exchange of the information between researchers and the synthesis of the ideas coming from various subfields of compact star physics. Looking into the future we have clear understanding that much can be achieved and improved on the path of mutual interaction between the subfields that were represented at the conference. The conference has had also a socially and culturally important impact in Armenia, by contributing to the festivities devoted to late Prof. Victor Ambarstumyan and bringing world reknowned scientist to this country.

Detailed information on the symposium including online posted talks, the program and a photogallery can be found at the conference web page:
https//th.physik.uni-frankfurt.de/~sedrakian/armenia08/

2. Scientific content and discussion

The first two full days of the the symposium were focused on the macrophysics of neutron stars. Dong Lai (Cornell) presented a general overview of the three topics with an emphasis on his own work: (i) isolated magnetic neutron stars (ii) accreting neutron stars (iii) merging neutron stars. The reasons of vastly different behaviour of neutron stars as seen for example on the P-Pdot digram is due to their rotation and magnetic fields. The equation of state of matter is strongly affected by fields in excess of 10^{13} Gauss. In the presence of Landau quantization the transport coefficients of electrons become strongly anisotropic, which eventually affects the thermal structure of neutron star's envelope and the emitted X-ray spectrum. It was then pointed out that the vacuum polarization can strongly affect radiative transfer in the envelopes of neutrons stars. Recent results on particle acceleration in the magnetosphere were discussed. On the topic of accretion onto strongly magnetized neutron stars the focus

was on the excitations of bending waves in a disk surrounding the star and its implications for quasi-periodic oscillations. It was then argued that neutron star binary inspiral wave-forms are sensitive probes of the equation of state of matter, in particular the number of so-called missing cycles is sensitive to the *radius* of the star. The topic of binary radiopulsars was continued by G. Bisnovaty-Kogan (IKI, Moscow), who after a short historical detour, focused on the issues of enhnced evaporation of pulsars in binaries, their role in constraining the general relativity and possible variations of the gravitational constant with time. He concluded that the timing of a binary radiopulsars is the most powerful instrument for the verification of General Theory of Relativity. The audience discussed the possibility and the need of including the variability of speed of light and other fundamental constants in the treatments discussed by Bisnovaty-Kogan. Recent numerical simulations of magnetorotational collapse were presented by S. Moiseenko (IKI Moscow). His focus was on the mechanism of supernova explosions, in particular on the magentorotational instability, jet formation, and the sensitivity of the collapse to the parameters, such as the core mass and rotation rates. He pointed out the possibility of breaking of symmetry in rotating case and formation of one sided jets. The discussion of the results stressed the need of three-dimensional simulations; in this discussion L. Rezzolla pointed out the possible effects of general relativity in this problems. A. Sadoyan (Yerevan State) discussed the results of the local group on the generation of gravitational waves by rotating white dwarfs. L. Rezzolla (AEI, Potsdam-Golm) presented the recent results of the numerical relativity group at the AEI on binary neutron star mergers. Starting with the numerical techniques that is employed in their study (including the codes Cactus and Wisky) he went on to discuss the mergers of unmagnetized neutron stars and (most importantly for the community of the nuclear and particle physics) the role of the equation of state (EOS) in the inspiral. So far the EOS is modelled in terms of simple polytropic EOS and this is compared with the ideal fluid EOS. The formation of black holes as a result of a merger was further discussed; the time-scale of the formation of black hole appears to be sensitive to both the EOS and the masses of the companions. Likewise the waveforms produced by low/high mass and polytropic/ideal EOS binaries were discussed. Further the Kelvin-Helmholz instabilities in high-mass binaries and the inspiral of magnetized binaries were presented. The discussion has stressed the fact that the models are still idealized; realistic equation of state, neutrino processes, instabilities, etc should be considered in the future. R. Spurzem (Heidelberg) presented results on the dynamics of the black holes in galactic nuclei. Simulations of their motions in a many body environment require large numerical effort and special software needs. The talk was both informative and educational with respect to the software development and the generation of gravitational waves by such systems. L. Grigoryan (Yerevan State) is interested in the alternative theories of general relativity, in particular in a variant of the Brans-Dicke theory developed by Rosen. He presented results for configurations of compact stars within such a theory. One remarkable outcome of his computations is that there is no maximum mass or black hole solutions in this type of gravity

theories, so that in principle very have compact objects can be obtained. Erich Gaertig (Tuebingen) presented recent results on the oscillations of neutron stars. His talk also included a detailed general introduction to the theory of stellar pulsations. The relevance of neutron star pulsations (astroseismology) was discussed in the context of generation and observation of gravitational waves. Modification of the modes due to the general relativistic effects were discussed. Further focus was on the effects of rotation on splitting of the modes. Continuing the issue of oscillations in neutron stars A. Sedrakian (Frankfurt U.) discussed the oscillations modes of vortex lattices in neutron stars and the long term variability of spins in neutron stars. The discussion focused on the alternatives in explanation of long term variabilities of pulsars including precession. Z. Osmanov (Tbilisi U.) discussed a model of a neutron star magnetosphere and pulsar winds. He argued that it is possible to achieve a force free regime by twisting the magnetic field lines, since the energy output by a typical neutron star through radiation is sufficient for this to occur.

The following day was devoted to a large extent to the quantum vorticity in neutron stars. B. Link (Montana State) presented his recent simulations of the vortex motion in a stack of parallel plates featuring impurities (assuming that the nuclear lattice is amorphous, so that the vortex symmetry can not coincide with the symmetry of nuclear lattice). His main conclusion was that even in the absence of dissipation there is a finite critical velocity needed to prevent a vortex from pinning to a nuclear site. This generalization of the earlier single segment calculation by A. Sedrakian rises the problem of the response of the superfluid to a glitch. The discussion included technical issue of boundary conditions and numerical solutions of stiff differential equations. M. Alford (Washington U., St. Louis) discussed the Ginzburg-Landau functional for a mixture of protons and neutrons in the case where neutrons are non-rotating. He studies this mixture as a function of the Ginzburg-Landau parameter and is interested in the implications of the background neutron superfluid on the transition from type-II to type-I superconductivity through the Bogomolny point. We discussed the issue of how such a set up can be realized in nature or in a laboratory; the perspectives of such realization in dilute atomic gases was vexed. K. Shahabasyan (Yerevan State) discussed vorticity in quark cores of neutron stars, in particular in the case where the quark matter is in the CFL phase. D. Sedrakian (Yerevan State) continued the issue of vorticity by presenting the covariant equations for magnetic vortices in superconductors. He discussed the relaxation processes accompanied by the motion of vortices when the magnetic field is changed abruptly. Classical vortices and generation of jets were discussed by M. Abrahamyan (Yerevan State). Although this topic has not found (yet) an application in neutron star physics, the flow of discussion did match the general theme. Finally, S. Popov (Moscow U.) discussed the population synthesis of neutron stars and their cooling. He pointed out that the Gould Belt population of stars may have impact on population synthesis. He further discussed the anomalous X-ray pulsars (the Magnificent seven).

September 22 was enteirly devoted to the nuclear physics of compact stars. J. Margueron (IPN, Orsay) discussed the superfluid properties of neutron star crusts,

including the role of the band structure induced by periodic lattice, BCS-BEC crossover for neutrons and the role of screening on pairing gaps. The key observable in these calculations is the specific heat of the crust, which should be important in the simulations of cooling of neutron stars. The discussion focused on the extension of the calculations to the isospin symmetric and asymmetric nuclear matter and further constraints through the comparison with the results obtained from finite nuclei. G. Roepke (Rostock U.) discussed the formation of light clusters in supernova envelopes which should be an important input for supernova simulations in general and formation of neutrino spectra in particular. He further discussed the condensation of alpha particles in finite nuclei. A. Illarionov continued the topic of many-body calculations for nuclear matter by presenting recent Monte Carlo simulations for neutron and (preliminary) results for symmetric neutron matter. We discussed the limitations of the Monte Carlo simulations to small number of particles and the way the spin is sampled. G. Alaverdyan (Yerevan State) discussed the EOS based on relativistic mean field approximations. G. Hajyan (Yerevan State) presented equilibrium figures of strange stars supporting large nuclear crusts. Short status reports of their PhD work was then given by P. Grygorov (Tuebingen U.) and D. Zablocki (Wroclaw U.). Groygorov discussed the neutrino propagation in neutron star crusts within the models developed in Tuebingen. D. Zablocki discussed BCS-BEC crossover in quark matter. During the last day of the symposium two talks by A. Saharyan (Yerevan State) and his student M. Mkhitaryan discussed the quantum effects (vacuum polarization) in higher dimensional space times. A. Harutyunyan (Yerevan State) presented results on superdense start containing strange quark matter. The closing talk was by H. Grigoryan (JINR, Dubna) on cooling of hybrid stars. The discussion focused on possible ways of distinguishing the stars containing quark matter from the purely hadronic stars.

3. Assessment of results and impact on future directions

The overall assessment of the symposium by the participants was very positive. As evidenced by the discussions at our meeting, compact stars represent a vibrant field with lots of interesting problems yet be solved. It became clear that there has been an impressive progress in the field over the past years, a progress to which the European scientist contributed substantially. One of the concrete results of the symposium is the collection of the talks that are posted on the web page of the meeting (see the summary on page 1). This information is publicly available. There are ongoing talks with several publishing houses in order to print the proceedings of this meeting. Another result of the meeting is that some of the existing collaborations among the participants have been continued. Finally, new collaborations were born out of the discussion at the conference.

As is evidenced be the presentations at the symposium the current state of the art of compact star physics is rather sophisticated, multi-level and multi-disciplinary. One general trend is that there is an increased numerical component in virtually every subfield that has

been discussed. Most sophisticated numerical methods are used to solve coupled (nonlinear) equations for gravity, hydrodynamics and magnetic fields in the field of numerical relativity. The quantum many body methods for the solution of the nuclear and quark matter problems in most cases employ non-trivial numerical methods (path integrals, Monte Carlo). Vortex dynamics was treated by solving a large number of coupled stiff differential equations. It is likely that this trend will continue. One of the keys in achieving progress is *further development of numerical methods and computers for problem solutions.*

A positive impact of the symposium is that we were able to find the points where the different fields overlap, the areas where the problem solving could be carried out using the expertise of workers from different subfields. Therefore, another future direction of the development of the field will be the synthesis of ideas and methods from various fields such as the numerical relativity, particle, and nuclear physics.

The symposium defined a number of directions for future efforts

- Physics of binary inspiral, improved treatments of equation of state, possible phase transition, magnetic fields and neutrino processes. What can be learned from the observation of gravitational waves from binaries about the parameters of compact stars?
- Physics of neutron star crusts, including the pairing properties, neutrino interactions and transport.
- Better understanding of clusters in subnuclear matter, medium modifications of light clusters, their condensation, and interactions with neutrinos.
- Vortex state in superfluid phase of compact stars, including vortex dynamics in random and crystalline structures, collective shear modes, vortex structure in color superconducting quark matter and in multicomponent systems.
- Cooling of neutron stars as a probe of their interiors, cooling of hadronic stars vs cooling of quark matter and strange matter stars. The role of surface layers in radiative transfer, temperature asymmetry, and the X-ray flux emitted from the surface.