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Report on the dissertation of Mikhail Evgen'evich Gusakov entitled "Dynamical processes in neutron stars" submitted for the degree of doctor of physico-mathematical sciences in scientific specialization 1.3.1. Physics of cosmos, astronomy.

This dissertation deals with neutron stars, the remnants of gravitational core-collapse supernova explosions of progenitor stars more massive than the sun. Neutron stars are not only the most compact celestial bodies known in the universe – the matter in their core is crushed at densities exceeding that found inside the heaviest atomic nuclei – but they also have the most extreme magnetic fields reaching millions of billions that of the Earth. Initially very hot, neutron stars cool down very quickly by releasing neutrinos and after a few days, their very dense nuclear matter is predicted to become cold enough for the occurrence of quantum phase transitions, such as neutron superfluidity and proton superconductivity. The outer layers of neutron stars are also expected to crystallize thus forming a solid crust. Mature neutron stars are therefore expected to have a complex internal structure and dynamics. The physics of these objects is very rich, as reflected in this dissertation.

The first chapter introduces the general context of this work and its relevance. The main research objective is to address the role of various dynamical processes taking place inside neutron stars and their astrophysical manifestations. To this end, more realistic models of neutron stars accounting for their complex internal constitution and dynamics have been developed by the candidate. The different contributions of the candidate are outlined and are discussed in more details in separate chapters. In each chapter, the state-of-the-art is briefly reviewed and the contributions of the candidate are clearly presented.

The second chapter is devoted to the multifluid hydrodynamics of nucleon-hyperon superfluid and superconducting mixtures as found in the core of neutron stars. The first achievements of the candidate are the calculations of the non-dissipative mutual entrainment coupling coefficients of neutron-proton superfluid mixtures for arbitrary temperatures. Calculations have been performed for both nonrelativistic and relativistic formulations of the multifluid hydrodynamic equations. More generally, the candidate has developed a system of kinetic equations describing superfluid mixtures in an external electromagnetic field and calculated the response functions to long-wavelength and low-frequency perturbations. Other key microscopic parameters determined by the candidate are bulk viscosity coefficients arising from nonequilibrium reactions. The candidate shows how bulk viscosity impacts the damping of sound modes. The calculations of the entrainment matrix and bulk viscosity coefficients have been extended to account for the presence of hyperons. With these models, the candidate studies sound waves in nucleon-hyperon superfluid mixtures and their damping. The candidate shows that diffusion can be an important dissipation mechanism in superconducting neutron stars.

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In the third chapter, the previous models are applied to study global oscillations of non-rotating superfluid neutron stars and their damping in full general relativity, taking thermal effects into account. The oscillation spectrum can be divided into normal modes as in non-superfluid neutron stars and superfluid modes. Unlike the former, the latter are found to be very sensitive to thermal effects. This is because the temperature in a neutron star can be comparable to the critical temperatures for the disappearance of superfluidity. The candidate proposes an accurate approximation scheme to calculate these modes and their dissipation timescale perturbatively after showing that they can be described by a system of two weakly coupled equations. The superfluid modes are found to decay much faster than normal modes except near resonances (avoided crossings). Moreover, the damping of normal modes can be substantially different from that calculated from the hydrodynamic equations of ordinary fluids. The candidate demonstrates that the so-called g-modes (whose restoring buoyancy force is associated either with composition or temperature gradients) can subsist in superfluid neutron stars at variance with previous expectations based on simplified models. Consequently, superfluid neutron stars could be prone to convection instability under certain circumstances. Finally, the candidate shows that oscillations modes can be strongly damped by diffusion.

Models of superfluid and superconducting neutron stars with increasing complexity are presented in the fourth chapter to account for the presence of neutron quantized vortices (arising from rotation) and quantized proton flux tubes (arising from the presence of a strong magnetic field). For this purpose, the classical smooth-averaged Hall-Vinen-Bekarevich-Khalatnikov hydrodynamic equations for superfluid helium-4 are here generalized to relativistic superfluid mixtures at arbitrary temperature in neutron stars. The candidate also derives the relativistic dissipative magnetohydrodynamics equations for both nonsuperfluid and superfluid mixtures for applications to neutron stars.

The oscillations of rotating superfluid neutron stars and their damping are investigated in the fifth chapter, focusing on the Rossby waves (so-called r-modes), whose restoring force is the Coriolis force. Because these modes are known to be unstable at any angular velocity and carry away angular momentum through gravitational-wave emission, observations of rapidly rotating neutron stars in low-mass X-ray binaries poses a theoretical challenge. The candidate explores different dissipation mechanisms to explain the suppression of the r-mode instability in neutron stars. One such mechanisms is the dissipation induced by nonequilibrium reactions involving hyperons. Alternatively, the candidate shows that the r-mode instability can be suppressed even in the absence of hyperons by the strong dissipation between normal and superfluid modes in resonance. To this end, the candidate has developed a new approach to determine the r-mode spectrum of superfluid neutron stars considering the effects of stratification and entrainment. He shows that resonant r-mode stabilization can solve the observational puzzle provided most neutrons in the core of a neutron star are superfluid. He also predicts the existence of a new class of neutron stars dubbed HOFNARs from “HOt and Fast Non-Accreting Rotators”).

Chapter six deals with the evolution of magnetic fields in neutron stars. Focusing first on strongly magnetized neutron stars (so called magnetars) for which superfluidity and superconductivity are not expected to occur, the candidate shows that the usual neglect of the fluid motions inside the star is unjustified. Accounting for these motions leads to an accelerated evolution of the magnetic field on a timescale comparable to the age of magnetars. The candidate then considers the role of superfluidity and superconductivity in ordinary pulsars. In these neutron stars, the evolution of the magnetic field is governed by the dynamics of proton flux tubes in their core. The candidate shows that the associated timescale is shorter than previously thought, thus questioning the common assumption of a frozen magnetic field.

In chapter seven, the candidate presents a new thermodynamically consistent theory of accreted neutron-star crusts. The accumulation of hydrogen-rich material onto the surface of a neutron star in low-mass X-ray binaries triggers X-ray bursts. The ashes are slowly buried inside the crust where they are further processed due to electron captures, neutron emission, and more speculatively pycnonuclear fusion reactions. The heat released by nonequilibrium reactions powers the thermal luminosity of neutron stars during quiescence and is also relevant for the interpretation of the thermal relaxation of the heated crust after the end of an accretion outburst. In the traditional approach of Haensel and Zdunik, neutrons emitted by nuclei are implicitly assumed to sink with them. However, the candidate shows that this assumption is unrealistic, and neutrons can also diffuse upwards. The candidate has developed the necessary formalism to take this effect into account and shows that neutron diffusion changes radically the structure and the properties of the inner crust of accreted neutron stars. The resulting equation of state is found to be not much different from that of cold non-accreted neutron stars, and the heat released is substantially reduced. The interpretation of observations thus needs to be completely revised.

The last chapter presents various results obtained by the candidate with the emphasis on the reduction of the nucleon pairing gaps in presence of superflow and heating induced by the spin-down of millisecond pulsars.

Overall, this thesis is well written and clear. This work covers a very wide range of fields from nuclear physics, condensed-matter physics, plasma physics, to hydrodynamics, general relativity, and astrophysics. The variety of research topics addressed by the candidate is quite impressive and shows a deep knowledge of the physics of neutron stars rarely encountered. His original contributions have shed a new light on many facets of these stars and have important implications for the interpretation of astrophysical phenomena. His numerous achievements have been published in major peer-reviewed international scientific journals including *Physical Review Letters*. For all these reasons, I strongly recommend awarding the degree of doctor of physico-mathematical sciences to the candidate.

Prof Nicolas Chamel