RESEARCH INTERESTS AND PAST ACCOMPLISHMENTS BY PAVEL DENISENKOV

My research has always been focusing on stellar physics. I am particularly interested in studies of mixing of products of nuclear reactions and transport of angular momentum in stars. I use available spectroscopic observations of chemically peculiar stars and improvements in the physics of stellar models to assess the impact of hydrodynamic mixing mechanisms and magnetic fields on surface chemical composition, photometric peculiarities, and rotation of low- and intermediate-mass stars. I have also been studying external dynamic and pollution processes, such as tidal interactions and mass exchange between stars in close binary systems, planet swallowing by red giants, and their effects on surface rotational and abundance anomalies in stars.

I have over 20 years of professional expertise in the following areas of theoretical stellar and nuclear astrophysics:

- Numerical modelling of the evolution of rotating
  - low-mass pre- and early main sequence (MS) stars (including the Sun);
  - low-mass red giant branch (RGB), horizontal branch (HB), and thermally pulsing asymptotic giant branch (TP-AGB) stars; I have proposed low-mass TP-AGB models in which internal gravity waves build up a sufficiently wide ^{13}C pocket for the solar s-process nuclides to be produced under radiative conditions;
  - intermediate-mass MS and TP-AGB stars with hot-bottom burning;
  - massive MS stars.
- Studying the kinetics of nucleosynthesis (with diffusion, wherever it is necessary)
  - in the pp chains (e.g., in relation to the problem of Li abundance variations in MS dwarfs, Li-rich K-giants, ^{3}He-driven thermohaline mixing, and the cosmological ^{3}He and Li abundances);
  - in the CNO, NeNa, and MgAl cycles (e.g., in relation to the problem of star-to-star abundance variations in globular clusters (GCs) and nucleosynthesis in Novae);
  - in the He-shell flash and following s-process in TP-AGB stars (related to the origin of abundance anomalies in the oldest stars in the Universe).
- Developing models of
  - internal and surface stellar rotation evolving as a result of angular momentum transport and mass loss;
  - non-convective mixing and angular momentum transport driven by rotational and other (magneto-) hydrodynamic forces and instabilities, such as meridional circulation, shear mixing, internal gravity waves, thermohaline convection, the Tayler-Spruit dynamo, the Lorentz force and magnetic buoyancy.

At present, the main tools of my research are the powerful state-of-the-art stellar evolution and post-processing nucleosynthesis computer codes MESA and NuGrid. They use multiprocessing and have up-to-date input microphysics and original numerical algorithms designed to model rotation, mass-loss, tidal interactions, angular momentum transport and mixing in stars. For multi-dimensional hydro- and MHD- numerical simulations, I have been using the COMSOL Multiphysics finite-element-method software package and a pseudo-spectral code designed for the solution of similar oceanographic problems.

At the end of the 1980s, I was the first to include the reaction ^{22}Ne(p,γ)^{23}Na in computations of H-burning phases of stellar evolution and to show that it could be responsible for Na abundance anomalies in giants. In particular, I explained the origin of Na overabundance and its dependence on the surface gravity and mass in yellow supergiants. I also noticed that, in metal-poor RGB stars, Na was produced in the vicinity of H-burning shell, where O was depleted in the CNO cycle. That finding together with the empirical evidence that RGB stars experience extra-mixing in a radiative zone between the H-burning shell and convective envelope were used to interpret the global O–Na anti-correlation in GC red giants. Our interpretation attracted great attention and initiated extensive spectroscopic studies of the chemical composition of GC stars at the McDonald, Lick, Mount Stromlo, Keck, and European Southern Observatories. It promoted further theoretical work on nucleosynthesis and extra-mixing in red giants as well as experimental search for other low-energy resonances in reactions of the NeNa and MgAl cycles.

The new spectroscopic studies have shown that the O–Na anti-correlation is also present in GC MS stars, therefore at least a part of it must be of primordial origin. As a result, the research has shifted toward revealing its primordial sources. I have been participating in this exciting quest by investigating intermediate-mass TP-AGB and low-mass binary stars as potential sources of this and other abundance anomalies in GCs. In particular, analysing the hot-bottom burning in an intermediate-mass metal-poor AGB star, we have made a robust prediction that Mg should have been depleted to a greater extent than O. Since this is not commonly seen in GC stars, our finding casts doubts on intermediate-mass AGB stars as the only primordial pollution source. This is one of the reasons why the search has recently turned to massive stars with rotation-induced mass loss and mixing.

In the meanwhile, empirical evidence has accumulated suggesting that the RGB extra-mixing actually operates in every low-mass star but that it only affects the Li, ^{3}He, and CN abundances. We have estimated its depth and rate in both field and cluster red giants of a different metallicity. These parameters have turned out to have approximately the same values in the majority of RGB stars, which prompted us to coin the term "canonical extra-mixing" emphasizing its universal character.

What is the physical mechanism for canonical extra-mixing? We proposed that it might be rotation-induced turbulent diffusion. However, low-mass stars do not seem to possess a sufficient amount of angular momentum by the end of their MS life as they loose it via a magnetized stellar wind. On the other hand, a much larger fraction of Li-rich stars among rapidly rotating K giants indicates that rotation may still be involved. We have interpreted this correlation as a result of the rare event when a red giant swallows its orbiting giant planet, which leads to its spin-up and enhanced extra-mixing. If the mixing rate were proportional to the rotational kinetic energy then the observed tenfold increase in angular velocity would make the mixing fast enough to produce a lot of Li via the Cameron-Fowler mechanism. In this scenario, the infrared excesses in spectra of Li-rich K giants are readily interpreted as dust emission by planet's debris. Another example of rapidly rotating red giants are primary components of the RS CVn binaries. They have been spun up by the tidal force. We have shown that their photometric (clustering on the lower RGB) and abundance (Na excess) peculiarities could also be caused by enhanced extra-mixing.

The most promising mechanism for canonical extra-mixing has been proposed recently by Charbonnel & Zahn. This is thermohaline convection driven by a μ-gradient inversion maintained by ^{3}He burning. However, first, we have shown that, in rotating stars, it has to be suppressed by horizontal turbulence. As a supportive evidence, we have found that thermohaline convection appears to be inefficient in carbon-enhanced metal-poor (CEMP) stars in which a μ-gradient inversion is produced by accretion of He- and C-rich material from their AGB binary companions. Besides, the ^{3}He fuel gets exhausted by the end of RGB evolution. This makes it difficult to understand what drives extra-mixing in low-mass AGB stars, signatures of which are seen in the CEMP stars as well as in presolar grains of AGB origin. Finally, our recent 2D and 3D direct numerical simulations of thermohaline convection in a low-mass RGB star have demonstrated that it has a mixing rate that is a factor of 50 lower than the observationally constrained rate of RGB extra-mixing.