FIRST-PRINCIPLES SIMULATIONS OF ELECTRON-POSITRON PAIR FORMATION IN PULSAR POLAR CAPS

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Neutron stars (NSs) – with sizes only $\sim$ 3 times larger than the Schwarzschield radius (radius of a black hole of the same mass), densities comparable to the density of atomic nuclei, and magnetic fields reaching (and exceeding) critical quantum field strengths – are the most extreme (stable) objects in the Universe accessible to our study. The extreme physical conditions inside and in the near vicinity of NSs could never be reproduced in Earth-based laboratories. Study of NSs offers a unique opportunity to test fundamental physical theories in the most extreme regimes. In order to tap this treasure trove of extreme physical conditions we need to understand now NSs produce the radiation we detect with Earth- and space-based telescopes.

The vast majority of known NSs are radio pulsars – sources of periodic radio pulses, though they are indeed truly multiwavelengths objects emitting radiation from radio to gamma. Pulsars are rapidly rotating highly magnetized NSs and all pulsar emission is generated by dense plasma in their magnetospheres. Discovered more than 50 years ago, they have remained a profound puzzle of the modern astrophysics, as their exact emission mechanisms are still not known. The most enigmatic is their radio emission mechanism. This is mainly because the radio emission is coherent, i.e. produced by microscopic magnetospheric collective plasma motion that is extremely difficult to calculate.

Plasma, the fourth state of the matter (besides solid, liquid and gas), is a very hot gas consisting of charged particles which interact at a distance, as opposed to normal gases consisting of neutral particles interacting only during their collisions. Pulsar plasma is of a very special variety, in contrast to “normal plasma” in stars, accretions disks, or planet ionospheres consisting of electrons and ions, it is comprised of particles and antiparticles: electrons and positrons. The electron-position plasma in the magnetosphere of a pulsar is created in polar caps, small regions near magnetic poles, in violent “discharges” involving extremely strong electric and magnetic fields.

Pulsar problem turned out to be extremely complicated. All attempts at creating adequate analytical descriptions for the structure of even an ideal pulsar magnetosphere, i.e. attempts to find the configuration of electric and magnetic fields in the magnetosphere, were unsuccessful. Without the knowledge of magnetospheric structure it was difficult to develop reliable models of pulsar emission mechanisms. The breakthrough in pulsar theory came with the advent of modern computers. In the first decade of this century the problem of the structure of the force-free pulsar magnetosphere has been solved via computer simulations. However, consistent reliable models of pulsar emission mechanisms are still missing.

In this project, we will study what happens during discharges creating the electron-positron plasma with the help of computer simulations utilizing so-called Particle-In-Cell (PIC) technique. In PIC, plasma is represented as a collection of macroparticles that carries charge and mass. The PIC method is the most fundamental way of modeling plasma physics which makes no approximations on the microphysical scale (at the expense of computational complexity).

The proposed dedicated simulations of pair discharges near pulsars will be the first of their kind. They will show how radio emission of pulsars is generated from first-principles, and how it propagates through the magnetospheric plasma. These proposed investigations, for the first time, will build a solid theoretical model of radio emission from pulsars. Predictions of simulations, e.g., spectral slopes and the geometry of the radio beam, will be compared with observations of pulsar radio spectra and lightcurves. We will also study how energetic particles produced in discharges heat the surface of the NS and how luminous these discharges are in gamma-rays.