Report for the project "**Collisional electron kinetics in the atmosphere of 67P Churyumov-Gerasimenko comet**" (DAAD-SPbU)

Project led by: **Dr. Andrey Divin** (St. Petersburg State University, Russia), andrey.div@gmail.com, a.divin@spbu.ru
German research leader: **Jun-Prof Dr Maria Elena Innocenti** (Institute for Theoretical Physics I, Ruhr-Universität Bochum, Germany), mariaelena.innocenti@rub.de

Previous studies of electron kinetics of the vicinity of a weakly outgassing comet [*Deca, 2017*], [*Deca, 2019*], [*Divin, 2020*] were performed using fully collisionless approach, meaning that collisions between separate particles (or species) are considered to be infrequent and might be neglected. Such approach allowed to investigate in detail acceleration of electrons by ambipolar electric field [Divin, 2020] and study electron trajectories [Sishtla, 2019]. Due to this acceleration, the solar wind electrons were found to have elevated energetic fluxes close to the nucleus. Electron pressure appeared anisotropic with temperatures (parallel to the local magnetic field) approximately several times the solar wind electron temperature. However, this approach ignored the presence of a dense neutral coma surrounding the comet, and corresponding collisions with neutrals.

According to the project plan, a Monte Carlo (MC) collision numerical scheme (that is, a model of electron-neutral inelastic collisions) was adapted for the use in cometary coma environments to study solar wind - outgassing comet interaction. The scheme is capable of tracing ions and electrons in a prescribed profile of neutral density needed to compute electron-neutral collision probabilities. For benchmark purposes, the numerical scheme was implemented in a Matlab prototype, which used the particle and field data of the original collisionless simulation, hence, this approach was not fully self-consistent. To be more specific, during the 2-months stay we developed:

Month 1
In cooperation with the host, we continued to develop and improve the prototype of the collisional module for the (originally collisionless) iPIC3D code. The prototype can only compute collisional effects in a small volume surrounding the comet since it's written in Matlab and not HPC compatible. The collisional operator contains a contribution of electron-neutral (water molecules) collisions and capable of modelling the energy loss of electrons due rotational, vibrational excitation, ionization and dissociation of water molecules. We found that the formed cold electron population can't stay (and accumulate for long time) very close to nucleus because the solar wind electric field drift pushes the magnetized electrons in the cometary wake.

Month 2
A library of classes was constructed compatible with the kinetic code iPIC3D. The library is based on the Matlab prototype. The library now contains an implementation of the MC collision numerical scheme which adds random fluctuations to particles' velocity at each time step, adding contributions of both acceleration and braking (cooling by collisions) in a self-consistent manner. To fully benchmark the code in three-dimensional regime, we applied for the HPC-Europa 3 computational time (see below).

Summing up our research, we confirmed that 1) introduction of collisions produces a population of low-temperature electrons in accord with observations and 2) resulting distributions are more isotropic than in pure kinetic simulations. Also, collisions do not suppress the most energetic electron fluxes even at higher cometary outgassing rates. An implementation of a Monte Carlo (MC) collision numerical scheme for iPIC3D code developed during this project, will be used in our subsequent studies of cometary comae, Solar chromosphere and collisional dynamics in other plasmas.

The project turned to be rather successful. **To extend the cooperation, we applied for joint grants**:

1) a joint DFG-RSCF (German-Russian) project was submitted aimed at studying the problem of energy transfer from the inner layers and photosphere of the Sun to the chromosphere, corona, and solar wind. The key objectives of the proposed grant are: to study the relationship between the global (MHD) and kinetic scales in the chromosphere, to evaluate the influence plasmoid instability or fractal reconnection on chromospheric heating, and to study the effect of partial ionization of plasma.
2) HPC-Europa 3 funded project for a brief (5 weeks in March-April 2022 if COVID permits) stay in Ruhr Universität Bochum. On top of that, HPC-Europa provided small-scale computational resources (~150k CPU*hrs on HLRS HPE Apollo (Hawk) system in Stuttgart) to benchmark/optimize the developed code and perform self-consisted 3D PIC simulations of electron cometary dynamics. These resources will help to greatly improve the results obtained within the current DAAD project.

List of references

1. Deca, J., Divin, A., Henri, P., Eriksson, A., Markidis, S., Olshevsky, V., & Horányi, M. (2017). Electron and Ion Dynamics of the Solar Wind Interaction with a Weakly Outgassing Comet. Physical review letters, 118(20), 205101
2. Deca, J., Henri, P., Divin, A., Eriksson, A., Galand, M., Beth, A., Ostaszewski, K. and Horányi, M., 2019. Building a weakly outgassing comet from a generalized Ohm's law. Physical review letters, 123(5), p.055101.
3. Divin, Andrey, Jan Deca, Anders Eriksson, Pierre Henri, Giovanni Lapenta, Vyacheslav Olshevsky, and Stefano Markidis. "A fully kinetic perspective of electron acceleration around a weakly outgassing comet." The Astrophysical Journal Letters 889, no. 2 (2020): L33.
4. Sishtla, C.P., Divin, A., Deca, J., Olshevsky, V. and Markidis, S., 2019. Electron trapping in the coma of a weakly outgassing comet. Physics of Plasmas, 26(10), p.102904, https://aip.scitation.org/doi/abs/10.1063/1.5115456