# Development of Micro-Macro Interaction Simulation Algorithm

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Proposed is the new simulation algorithm that can deal self-consistently with the whole natural and industrial system including microscopic and macroscopic processes. As an example, we developed the simulation code revealing the auroral arc formation that consists of the macroscopic interaction of the magnetosphere and ionosphere in the scale of 100,000 km, and the microscopic interaction among electrons and ions in the scale of 10 cm. The simulation results show not only a realistic striated auroral arc structure as a specific example, but also the potentiality of the holistic simulation in the various scientific and industrial fields.

**Keywords**: Micro-Macro interaction, Holistic simulation algorithm, Multi-Scale, Multi-Physics, Next generation simulator

## 1. Introduction

The Earth Simulator has made it possible to deal with a system in the scale range of several thousand in the three-dimensional simulation, which corresponds to $10^{10}$ grid points in three-dimensional space. The resolution of this order would be a good enough to deal with the entire system described by a single physical process. Regarding the global atmospheric circulation, for example, it can be resolved in the range of 10,000 km to a few km, and the behavior of the typhoon can be analyzed. The real climate dynamics is, however, governed by the cloud formation process in terms of the state change equation system of which spatial scale is between 1 $\mu$m and 1 mm, as well as the atmospheric dynamics governed by the Navier-Stokes equation. Therefore, in order to clarify the climate phenomena in more realistic way, we have to execute the simulation of both much different spatial scale and different physics. This situation is the same as the other phenomena, such as bio-system, plasma physics and so on.

The purpose of this project is to develop a holistic simulation algorithm named as "Micro-Micro Interaction Simulation Algorithm", which can solve the phenomena with the completely different time and spatial scale in different physical laws, simultaneously.

## 2. Concept of Micro-Macro Interaction Simulation

The organizing systems of the nature including industrial products are governed by the plural physical processes which are weakly but firmly interacting to each other. The Micro-Macro Interaction Simulation can deal with such the organizing system.

Suppose, for simplicity, a system that two processes, microscopic and macroscopic processes, are mutually interacting to each other. Weakness of the mutual interaction allows us to make simulations of both processes rather independently. We have already been able to simulate one physical process with enough resolution. Therefore, we need to exchange the information (data) between macroscopic and microscopic processes for the weak interaction. From the standpoint of the macroscopic process, data are not necessary at every microscopic unit time step to be transferred from the microscopic part, because there would be no appreciable macroscopic change of state in such a tiny time scale. On the other hand, from the microscopic standpoint, data are not necessary to be transferred at every macroscopic unit time step from the macroscopic part, because in such a short time scale the macroscopic state would not suffer any meaningful change at all. A reasonably small macroscopic time would be a reasonable data exchange period, because the microscopic process could be appreciably influenced by an appreciable change in the macroscopic state in a small macroscopic time step and also the macroscopic process could be influenced by an appreciable change in the microscopic state in that time step. By this way one can drastically reduce the data transfer rate.

Since we are concerned with the evolution of the entire system, the macroscopic simulation is the primary target. So, we start a macroscopic simulation in the traditional manner. Generally, an interesting phenomena where the microscopic process plays an important role in macroscopic evolution such as the formation of clouds, is when the macroscopic (environmental) state is changed drastically at local regions, consequently the microscopic process also being strongly activated. We do not have to make microscopic simulations at all grid points, but that it would be enough to pick up several featuring grid points of the macroscopic grid system. Thus, we can reduce drastically the number of grid points that should be subjected to microscopic simulation.

## 3. Quiet Auroral Arc Formation as An Example of Micro-Macro Interaction Simulation

As the first trial of the micro-macro interaction simulation, we started by the quiet auroral arc formation. The fundamental origin of the quiet auroral arc is the feedback interaction between the magnetosphere and ionosphere, of which scale is of the order of 100,000 km (see Fig. 1). Due to the macroscopic interaction, the striated structure of the electric current is formed in the ionosphere [1, 2]. When the electric current (electron beam) exceeds some critical value in somewhere near the ionosphere, the large potential gap, in other words, the large electric field along the geomagnetic field line is created by the microscopic instability through the particle interaction among electrons and ions of which scale is 10 cm [3, 4]. Such large electric field accelerates the low energy (100 eV) electrons up to 1 kev, which collide with the neutral atoms in the atmosphere to make auroral green (oxygen) or red (nitrogen) light. And also, such accelerated electrons ionized neutral atoms in the ionosphere, so that the ionospheric condition, therefore, the condition of the macroscopic interaction would be changed.

We employed the magneto-hydrodynamic (MHD) simulation for the macroscopic interaction between the magnetosphere and ionosphere, and the particle simulation in the open

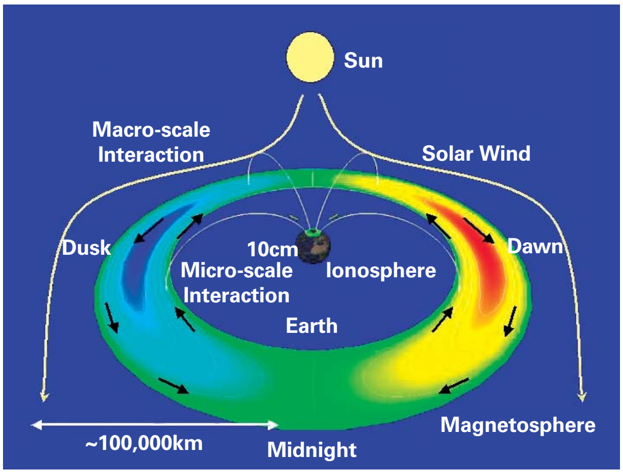


Fig. 1 The whole system of macro-scale and Micro-scale interaction

boundary condition for the microscopic interaction. Here, we also developed a new coordinate system, the dipole coordinate system, for the MHD simulation to get more realistic configuration of the magnetosphere [5].

As the boundary condition of the MHD simulation, we employed the fixed magnetospheric equatorial plane with a Heppner-type twin vortex plasma flow that works for the driving force of the feedback coupling between the magnetosphere and ionosphere. The ionosphere is described by the height-integrated ionospheric equations in which the Pedersen and Hall conductivities are taken into account. For the particle simulation, the open boundary condition is employed, where ions and electrons can freely flow into the simulation box and go out.

Starting the MHD simulation, we observed the striated structure of the electric current in the ionosphere as the time goes by, and the electron beam velocity exceeded the critical value that corresponds to 70% of the electron thermal speed. Then, using the information of the electron beam velocity, we made a shifted Maxwellian distribution function as an initial electron velocity distribution as well as the boundary condition on the upstream side, and started the particle simulation. During the execution of the microscopic (particle) simulation, we continued the macroscopic (MHD) simulation, because the macroscopic data such as the current is changed in the macroscopic time scale, in other words, the microscopic boundary condition on the upstream side is not changed in the microscopic time scale. After the electrostatic potential was formed due to the microscopic interaction and saturated, the information of the accelerated electrons was transferred to the macroscopic simulation, and was put into the ionospheric equation of the macroscopic simulation. Such simulation procedure was repeated, and thus, the simulation of the aural arc formation was done self-consistently from both macroscopic and microscopic viewpoints.

It should be emphasized that there are two important points of the micro-macro interaction simulation algorithm. One important point is that the microscopic simulation is executed only in the place where the electric current exceeds a critical value, not the everywhere. Therefore, we can largely reduce the calculation quantity. The other point is that the information to be transferred is very small. The current intensity at one grid point is given from the macroscopic simulation to the microscopic one at one time, and only the beam velocity and electric potential difference are yielded from the microscopic simulation to the macroscopic one. Therefore, it takes very small time to transfer the information.

## 4. Results of the auroral micro-macro interaction

When the beam electron velocity and the electric potential were given from the microscopic simulation, we calculated simultaneously how many neutral atoms were excited to transmit their own light as well. Then, we observed the auroral arc formation seen from the space and ground, which are shown in the right and left panel in Fig. 2, respectively.

### 5. What Comes Next

We succeeded the self-consistent simulation of auroral arc formation. Then, we are now preparing to develop the other micro-macro interaction simulations. One is the climate simulation in which both the atmospheric circulation and the more realistic raindrops formation is taken into account. The second one is the coupling of the fluid dynamics and the chemical reaction such as the behavior inside the automobile engine, and the third is the structure analysis from the microscopic process to the macroscopic one.

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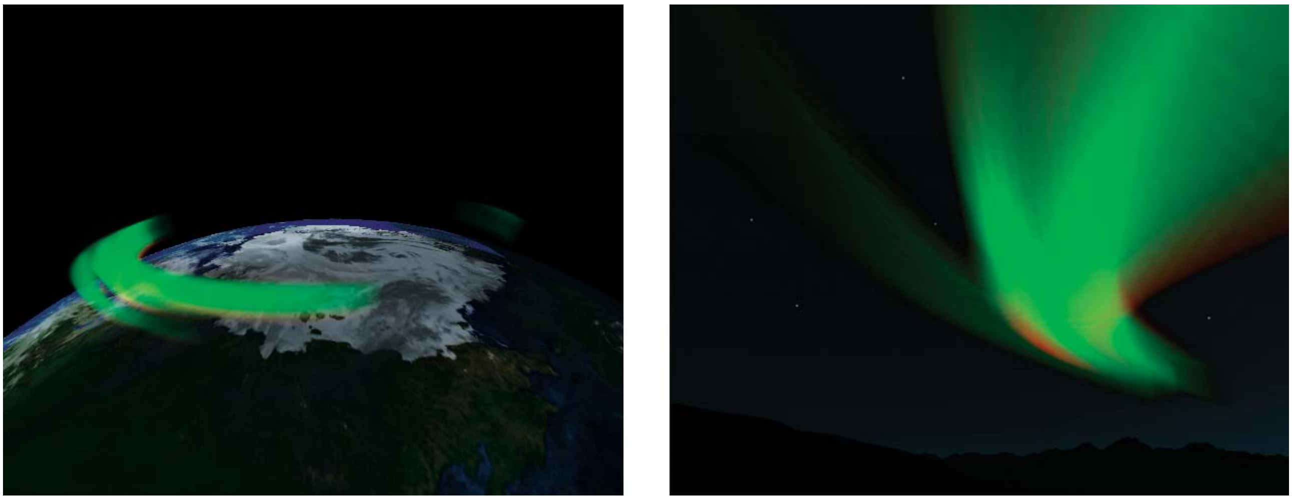

Fig. 2  The simulation results of auroral arc formation

# 連結階層シミュレーションアルゴリズムの開発

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自然界・産業界における様々な現象は、空間スケール・時間スケールが大きく異なるだけでなく、異なった物理法則に支配されている。例えば、気象現象を考えてみると、流体運動方程式に従った数kmから全球1万km規模の大気の大循環だけにはとどまらず、雨粒の生成という1 μmから1 mm規模の相変化が重要な役目を果たしている。従って、気象現象は、スケールにして少なくとも100億倍の違いがあり、しかも異なった物理法則を自己無撞着に解くことによって初めて、現実的なシミュレーションが可能となる。このような例は、地震や核融合、自動車などの産業製品など、枚挙にいとまがない。本プロジェクトの目的は、ミクロな物理過程とマクロな物理過程を統合した、全系を自己無道着に解明する全く新しいシミュレーションアルゴリズム、連結階層シミュレーションアルゴリズムを、様々な問題に対して具体的に開発し、そのことを通して、連結階層シミュレーションアルゴリズムの普遍化を図ることにある。このシミュレーションアルゴリズムは、多くの複雑現象の世界が階層に分かれている、すなわち、情報（エネルギー）は時間・空間的に一様に広がっているのではなく、局在しているということを利用して、現象を解明しようというものである。本年度は、その一例として、10万km規模の磁気圏と電離層の相互作用と10 cm規模の粒子間の相互作用の結合から起こる、オーロラの発光現象を自己無撞着に解明するシミュレーションコードを開発し、シミュレーションを実行した。シミュレーション結果は、具体例としての現実的なオーロラの発光現象の再現に成功しただけでなく、連結階層シミュレーションアルゴリズムの自然科学分野、産業分野への展開の可能性を示唆している。

キーワード：ミクロ・マクロ相互作用，連結階層シミュレーションアルゴリズム，マルチスケール，マルチフィジックス，次世代シミュレータ