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論文内容の要旨

In this thesis, presented are the development of an open boundary particle simulation code and a formation of the double layer under the open configuration.

Studies on the ion-acoustic double layer were performed by Sato and Okuda's particle simulation. However their simulation models are the simple periodic case or the field-opened system (with external constant voltage source). Their results indicated that the amplitude of the double layer is smaller than realistic one, for example, the generation mechanism of the high energy particle such as the auroral electron.

In order to treat the system as more realistic situation, where the terget plasma contacts with the external constant current source along the magnetic field line, a new open particle simulation argorithm is developed. Namely, the auther's particle simulation model is applicable to a system in which the internal plasma smoothly contacts with an external plasma source such as a current generator. The internal system can exchange both the energy and constituent with the external system. In other words, the whole system can be treated as the grand-canonical system from the thermodynamical viewpoint. The author presents the formalism and examine the range of applicability of the procedure. The scheme assures a balance between the outgoing and incoming particle flux through the boundaries at each time step.

Based on the above open simulation model, the ion acoustic instability under the one-dimensional electrostatic open configuration has been investigated, so that the ion acoustic double layer (IADL) can be formed. The condition of the formation of the IADL has to satisfy (a) the minimum average drift velocity:$v^e_{drift}/v^e_{th} > 0.3$ and (b) the minimum system length(L): $L > 512\lambda_D$.

The features of the generated IADL in the early phase of the temporal evolution under the open configuration are as follows: a stepwise type of the potential jump is formed and its maximum amplitude is the order of electron thermal energy, $\surd$-like potential structure, the minimum physical length, transient life, and so on. These features are similar to those in the closed (simplified periodic) and semi-open (filed-opened and particle-closed) systems which were shown by Sato and Okuda[1979]. The author found that this IADL structure is not maintained and is destroyed via the ion-Landau dumping mechanism. He also found that IADL under the open system is generated and destroyed repetitively.

The author discovers a new phenomenon in an open system, which can be named as "the super ion acoustic double layer." The super IADL exhibits such characteristics as the $\surd$-like potential structure and the minimum physical length. However, the prominent difference between the normal and super IADL is the magnitude of the DL potential gap. The potential gap of the super IADL in a typical case reaches up to more than ten times larger than the initial thermal energy of electrons, when the mass ratio is 100. This implies that when the thermal energy of electrons is 200eV, then electrons can be easily accelerated to several keV energy by the super IADL through the highly nonlinear evolution of the ion acoustic instability. This fact may account for the auroral electron acceleration which has been observed but remains as one of unexplained issues in space physics. Thus, an extremely large collisionless dissipation, in other words, anomalous resistivity arises.

It is found that the transition mechanism lies in the nonlinear driven electron-ion two-stream instability which is generated by locally accelerated electrons during the evolution of the normal IADL. The normal and super IADL are generated and destroyed repetitively. Namely, the IADLs under the open configuration does not reach to a stationary and monotonic state. The simulation runs through a long time reveal its repetitive appearance and disappearance of the super IADL. The life time of the super IADL is roughly 500 $\tau_{pe}(\tau_{pe} = 2\pi/\omega_{pe})$ which is much longer than normal IADL.

A super IADL is self-exited when the drift velocity $v^e_{drift}/v^e_{th} \geq 0.5$, and the maximum amplitude of the double layer has a strong dependence on the drift speed. In fact, when the drift velocity is taken as $v^e_{drift}/v^e_{th} = 0.7$, the generated potential gap reaches up to 45 times larger than the initial electron thermal energy.

Through the diagnosis of the kinetic entropy, the entropy production rate is maximized as the DL is being formed, while it is minimized when the DL structure is destroyed. In the open system, a negative entropy production occurs in accordance with the destruction of the generated DL potential structure, while the entropy production rate in the closed system is always positive. Namely, an unexpected highly ordered structure (IADL) is spontaneously created when a fresh free energy is externally supplied, and a generated entropy is expelled towards the surroundings.

Through the comparison of the temporal evolution of the kinetic entropy between the closed (periodic), the semi-open (field-opened and particle-closed), and the open system, the author satisfied that the destruction mechanism of the normal type of the IADL is the ion-Landau dumping mechanism. The fact indicates that the description of the kinetic entropy is extremely useful representation of the self-organization process.

Through the comparison between MHD self-organization and kinetic self-organization processes, the scenario of the self-organization is found to be essentially the same. In the open system with continuous energy inputting condition, the ordered structure can be realized and its structure is repetitively or intermittently generated and destroyed in both MHD self-organization and kinetic self-organization processes.

The common scenario of self-organization is that the self-organization takes place in an open system when (1) the free energy is continuously inputted, (2) a global instability is excited, (3) a localized energy conversion takes place, and (4) an enhanced disorderliness (entropy) is emitted.

This thesis contains four key-points. Firstly, generalized particle simulatin model under the open system is develped. Secondly, a new physical phenomenon named "super ion-acoustic double layer" is found. Thirdly, one candidate of the auroral particle generation mechanism is presented. Finaly, from the generalized viewpoint of the kinetic self-organization, one important scenario is presented.

論文の審査結果の要旨

本論文は、外界から定常な電流、すなわち、系外から系内に電子が定常的に流れ込む場合における、超イオン音波ダブルレイヤの生成の発見と、その形成機構を明らかにしたものである。通常のイオン音波ダブルレイヤは、1979年に佐藤等の手によって行われた粒子シミュレーションによって見出されている。しかしながら、佐藤等が用いたモデルは、単純な周期境界条件あるいは、定電圧源を境界に配置した場合のもので、得られたダブルレイヤポテンシャルの振幅は小さく、例えば、オーロラを光らせるような大きな運動エネルギーを持った高速の電子の生成を必ずしも説明し得るものではなかった。

今回、申請者は、オーロラ層上空の宇宙空間にみられるような定電流源に接したプラズマという、より現実に即した境界条件、即ち、粒子が境界を通じて自由に移動できるような開いた系を対象とした、全く新しい開放系粒子シミュレーション・アルゴリズムを開発した。また、このモデルは、核融合プラズマで今後重要な課題となる周辺プラズマ領域、特にダイバータ領域のプラズマ現象を明らかにするために必要不可欠な一般化された開放系モデルでもある。

このシミュレーション手法を用いて、長時間にわたるプラズマの非線形発展を詳細に調べた結果、今まで知られてきたイオン音波ダブルレイヤよりも、そのポテンシャルの振幅が数十倍に達するダブルレイヤ構造を世界で初めて発見し、これを「超イオン音波ダブルレイヤ」と名付けた。この発見は、オーロラ電子などの粒子の加速機構の解明に大きな寄与を果たしたといえる。本論文では、通常のイオン音波ダブルレイヤが生成・崩壊を繰り返しながら、局所的な電子加速を引き出すこと、また、その結果として発生した速い電子の流れによって二流体不安定性がプラズマ自身によって引き起こされることを示し、通常のイオン音波不安定性とプラズマ自身によって生起された二流体不安定性によって超イオン音波ダブルレイヤができるという生成過程を解明している。電子の初速度（定常的に与えるエネルギー）と形成されるダブルレイヤ・ポテンシャルの振幅との関係なども明らかにした。

更に、申請者は、開いた系におけるダブルレイヤ構造の形成を、自発的秩序構造の形成、即ち、「自己組織化」の観点から見直すために、運動論的エントロピーという量を導入し、時間に対するイオン及び電子のエントロピー生成率の変化から、構造が生成されるときに、エントロピーの生成率は極大になるという非常にユニーク且つ示唆に富む議論を展開している。また、超イオン音波ダブルレイヤが間欠的に生成・崩壊する特徴を、定常的にエネルギーが系に加えられた場合の「自己組織化」の普遍則の一端と考察している。それ故、この研究の意味するところは、単に表題となっている「超イオン音

波ダブルレイヤ」という面からみた特定研究の成果にとどまらず、プラズマ物理を越えた他の広範な分野における自己組織化研究、複雑性の科学に一つの大きな貢献をなすもであると考えられる。

従って、論文審査の結論として、本論文は博士論文としての価値を十分に有し、合格であると判断する。