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学位（専攻分野）	博士(学術)
学 位 記 番 号	総研大甲第269号
学位授与の日付	平成9年3月24日
学位授与の要件	数物科学研究科　核融合科学専攻 学位規則第4条第1項該当
学 位 論 文 題 目	自己組織化における外的制御の研究
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論文内容の要旨

Plasma is a typical example of complex systems where the state becomes easily far from equilibrium and highly nonlinear, namely, a medium of complexity. Sato and his colleagues have been studying "Self-Organization" in plasmas by means of computer simulation from a viewpoint of "Science of Complexity". They have clarified various examples of self-organization, from micro-scale(on a particle scale) to macro-scale(on a fluid scale), and proposed a general scenario of self-organization.

In this scenario, the free energy which is deposited, instantaneously or continuously, in a system drives a structural instability. As the structural deformation develops due to the structural instability, the energy exchange occurs between the magnetic energy, kinetic energy, and thermal energy, and simultaneously the enhanced entropy production is made through the nonlinear process, forming an ordered structure in the system. Finally, the ordered structure is maintained by expulsion of the unnecessary entropy. When the excess free energy is stored in the system, or the free energy is injected continuously into the system, the structural instability is again triggered to form the other ordered structure.

There are three key elements which play important roles in this scenario of the self-organization:

i) Nonlinearity of the system,

ii) Information (energy) input into the system,

iii) Entropy expulsion from the system.

The previous simulation studies have discussed that when a system is instantaneously pumped up to a higher energy state (instantaneous energy input), the system relaxes stepwise toward a minimum energy state and stays in that state for a long time, unless any additional energy supply is provided. In contrast, when it is continuously and directly fed from an energy source (continuous energy input), the system exhibits an intermittent or recurrsive excursion over local maxima and minima of energy state.

As for the example of the former case (instantaneous energy input case), Horiuchi *et al.* showed the relaxation and resultant self-organization of the magnetohydrodynamic (MHD) plasma. In this study, the magnetic field whose configuration is initially set in an unstable equilibrium state (in a high energy state) drives a kink instability and is relaxing stepwise towards a simpler configuration in the minimum energy state, making a nonlinear driven reconnection with each other. The resultant ordered structure of the magnetic field in a force-free equilibrium state is maintained.

Regarding the latter case, Amo *et al.* made the simulation study of the twisted magnetic flux tubes. They showed that when continuously twisted, a magnetic flux tube suffers a knot-of-tension instability, and undergoes rapid reconnection with untwisted field lines, whereby a burst energy release takes place intermittently. The twisted flux tubes reconnect with one another again to return to the original structure, and the whole process is repeated.

The purpose of this work is, as an extension of the self-organization study, to construct a nonlinear simulation model in which the energy input time and the dynamic response time of the system are changeable, and to examine the general scenario of self-organization proposed by Sato *et al.*, specifically from a view point of the relationship between the energy input into the system and the nonlinearity of the system.

To satisfy this purpose, developed has been a nonlinear simulation model in which a viscous membrane is devised between a steady energy source and an unstable feedback system, and both the time-scales of the energy input to the system and the dynamic response of the system are controllable. Using this model, it is examined how the stability and structure formation of the nonlinear system are controlled by the membrane that is able to adjust the inflow and outflow between the energy source and the feedback unstable system.

As for the feedback system a dissipation-free magnetohydrodynamic plasma coupled with a resistive weakly-ionized plasma is employed, which is based on the ionosphere-magnetosphere coupling model for the quiet auroral arc formation. That is, the Alfven wave driven by the convection energy in the magnetospheric equatorial plane propagates to the ionosphere, accompanying the field-aligned current. The Alfven wave excites the density wave in the ionosphere and propagate back to the magnetosphere. Thus, the feedback system is established through the coupling of the Alfven wave of the magnetosphere and the density wave of the ionosphere, and a feedback instability is realized.

The simulation model consists of three regions. The upper one is a thin viscous region (membrane) that converts the external convection flow energy into the system. The energy input rate to the system can be controlled by changing the viscosity. In the limit of the infinite viscosity, the viscous membrane acts as a fixed energy input source.

The bottom region is a thin dissipative layer where the energy converted into the system is dissipated as the Joule loss. The intermediate region is filled with an ideal magnetohydrodynamic plasma where a uniform magnetic field is immersed perpendicularly to both the viscous membrane and the dissipative region. Thus, Alfven waves carry information along the field lines between the viscous membrane and the dissipative layer. The dynamic response time of the system may thus be represented by the Alfven transit time.

The viscous membrane dynamics is described by the viscous MHD equations, where the plasma mass density and plasma temperature are assumed to be constant in time and discard the contribution of compressional modes. For the non-dissipative region, MHD equations without viscosity are solved.

In the dissipative region (thin layer), the current consists of only the collisional currents that flow perpendicularly to the magnetic field, namely, Pedersen and Hall currents. The field-aligned current carried by the Alfven wave is converted into these collisional currents in the dissipative layer to satisfy the current closure condition. The plasma density in the dissipative region is determined by the density continuity equation in which the effects due to the field-aligned current and recombination are taken into account.

At the outer boundary of the viscous membrane, a steady twin-vortex flow is imposed as a driving source. Then, the twin-vortex flow excites an Alfven perturbation which propagates through the non-dissipative region towards the dissipative slab along the field lines. When the Alfven perturbation arrives at the dissipative slab, the field-aligned current carried by the Alfven perturbation excites a closure perpendicular current and an electric field. The boundary electric field reflects back to the viscous membrane through the non-dissipative region. The reflection rate is determined by the ratio of the resistance of the dissipative region to the characteristic impedance of the non-dissipative region.

The simulation results show that there are two time-scales for the energy input, i.e., the time-scales for the dc and ac energy input. The dc energy input time-scale is determined by the thickness of the viscous plasma region and balances with the energy dissipation in the dissipative plasma region. The ac energy input time-scale, on the other hand, is determined by the wave length of the Alfven wave propagating through the non-dissipative region. Since the wave length of the Alfven wave is much larger than the thickness of the viscous region, the ac time-scale is much longer than the dc one.

Because of this character of the membrane, the thin viscous boundary layer (membrane) acts as a high-pass filter that can play a role of a fixed boundary for the dc component but a free boundary for the ac component. As a result, when the ac energy input rate becomes relatively small, the membrane acts to release the fluctuation energy (ac) from the system. In other words, the positive feedback effect for the fluctuation is weakened and the structure formation is prevented as the ratio of the dynamic response time to the ac energy input time becomes below a certain critical value, while an ordered structure formation is realized when the ratio becomes greater than or comparable to the critical value. Thus, branching for the structure formation is essentially determined by the ratio of those time-scales.

It is also found that the viscous membrane plays another important role in self-organization, namely, that as the structure formation is highly progressed, the dc energy input rate is autonomously adjusted so as to keep the developed structure in a steady form. This feature makes a marked difference from that of the previous studies on self-organization where the structure formation occurs intermittently. In the previous work of Amo *et. al.*, for example, they treated the case where the external twisting force of the magnetic field lines is directly imposed on the system, hence, the twisting rate is constant in time and independent of the state of the system. Because of this constant twisting, the deposited free energy in the highly nonlinear system is released intermittently and the structure is also intermittently changed. In contrast, the simulation model shown here demonstrates that the existence of an adjustable membrane can control the energy input autonomously so as to keep the obtained structure in a steady state. Namely, the existence of the viscous membrane for the energy input, which is quite natural in the actual plasmas, play a crucial role in the structure formation and its maintenance in the system.

論文の審査結果の要旨

本論文は、外界から薄い粘性層を通して連続的にエネルギーが供給される開いた系での自己組織化に対して、その粘性層の果たす役割を明らかにしようとする基礎的シミュレーション研究である。このような粘性層の存在は特殊なものではなく、むしろ太陽表面や磁気圏境界面など実際のプラズマ系においてはごく普遍的な存在であると考えられる。

本研究では、具体的モデルとして、オーロラアークの自発的構造形成機構を念頭において、電離層、磁気圏と太陽風に対応して、それぞれ弱電離プラズマ領域、完全電離プラズマ領域及び対流構造を持つ外部エネルギー源を設定し、完全電離プラズマ領域と外部エネルギー源との間に粘性層を介在させる、独創的な自己組織化模型を構築している。そしてシミュレーションを行うことにより、粘性層が、交流的あるいは直流的エネルギー供給に対し、自律的にエネルギーの流入制御を行う、ある種の半透膜のような働きをする事、その結果、自己組織化が進むか進まないかに関し、粘性層が決定的役割を果たすこと、さらに、系内部で構造が十分発達すると、その粘性層が外部からのエネルギー供給を調整する働きをすることなどを明らかにした。すなわち、本研究は、粘性層（膜）の存在が構造形成の成否や発生した構造の安定性を左右する、言い換えれば、エネルギー調整膜の持つ自己組織化の淘汰機能と安定化機能という、自己組織化研究に大きな一石を投じる結果を提示している。

本論文は、何かある現象を解明しようという従来型の研究ではなく、「複雑性の科学」の中心的テーマとも呼ぶべき「自己組織化」の普遍的法則を明らかにしようとしているところに本質的な価値がある。それ故、この研究成果が意味するところは、単に表題となっている外的制御という面からみた特定の研究成果にとどまらず、他の広範な分野における研究に大きな貢献をなすもの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、合格であると判断した。

次に、審査委員全員が論文内容、及び、プラズマ物理学、シミュレーション手法に関連した事柄など、様々な角度から質問を行い、それに出願者が答えるという形式で面接を行った。

その結果、研究の目的と方法論、及び、研究結果に対して、出願者が自己組織化研究の現状を把握し、今回の博士論文で明らかにされた新しい発見とその意味するところを的確に理解していることが認められ、自己組織化に見られる普遍性に対する考察も審査委員を納得させるものであり、他の広範な分野における研究に大きな貢献をなす独創的な研究であると判断された。また、質疑応答を通して、関連分野の知識も十分に有していることが明らかになった。さらに、提出された英文の論文要旨から、英語文章力についても十分な実力を具備していると認められた。よって、審査委員会は、出願者が試験に合格であると判断した。

以上の審査の結果、博士論文審査委員会は、本論文が博士論文として合格であり、出願者が学位を授与されるに十分な能力を有していると結論した。