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論文内容の要旨

" Complexity" is becoming a common concept in a variety of science fields; in biology, in chemistry, in physics, and even in social science. Self-organization, which is a process that creates an orderliness in nature, is a central theme of complexity. The principal aim of this study is to make an advancement in the construction of an integrated view of self-organization which is only crudely defined. The study of self-organization has so far been concentrated on the situations where an initial nonequilibrium state relaxes into a stationary minimum energy state in a transient fashion because of relative easiness of tractability. In this paper we conside self-organization in an open system where a free energy is continuously supplied from an external world. Specifically we adopt a system of twisted magnetic flux tubes. A twisted magnetic flux tube is widely observed in laboratory and astrophysical plasmas and it is believed that the temporal development of flux tubes is governed by their footpoint motions. Many authors have attempted to reveal the energy conversion process in the magnetic flux tubes twisted by their footpoint motions. Nevertheless the nonlinear development of continuously twisted magnetic flux tubes has not been well understood because of the difficulty in fully resolving the nonlinear process by the mathematical methodology alone. Some computer simulations have been performed so far, but its complicated and complex three-dimensional nonlinearity has shown an unexpectedly large resistance against our challenges and its dynamical evolution remains unveiled as yet.

To investigate the dynamical problem of the continuously twisted flux tubes, particuularly the energy relaxation process and the topological change of the magnetic field, elaborate three-dimensional magnetohydrodynamic （MHD） simulations have been performed. Te simulation system consists of a rectangular cylinder surrounded by a conducting wall and is filled with MHD fluid with an uniform axial magnetic field. A twisting motion, which is the energy source to the system, is applied continuously at both ends of the cylinder, thus the magnetic field lines are kept on twisting. An excess magnetic energy is accumulated in the system as the twist goes on. When the flux tube is largely twisted and free energy is sufficiently stored, its structure becomes unstable to kink modes.

Triggered by the instability, the magnetic field lines are largely deformed like a knot-of-tension instability of a bundle of twisted rubber strings. A singular current layer is formed between the deformed twisted flux tube and the surrounding untwisted magnetic field. Reconnection is driven at the singular current layer and the deformed flux tube reconnects with the surrounding straight magnetic field. Thus, the topology of the magnetic field is drastically changed. Through these processes, a large fraction of the stored magnetic energy is converted into the thermal energy and the kinetic energy. Because of the temporal change of the nonlinear susceptibility of the system, the energy transfer rate （Poynting Flux） form the continuous twisting motion of the boundary changes with time. When the excess energy is released, the system again absorbs more energy from the twisting motion and a similar relaxation process is repeated. In order words, a burst-like relaxation appears intermittently. Interestingly, after several intermittent burst-like relaxations, the magnetic field structure returns to the initial state. Then, a recurrent behavior is reproduced in the topological change of the magnetic field. The recurrent feature is also seen in the temporal variation of the energy conversion process.

Interacions among twin and quartet twisted flux tubes are also studied in detail. The twisted flux tubes become unstable simultaneously, and each tube approaches one another and collides. Then singular current layers are formed on the contact surfaces of the colliding tubes and strong reconnection is triggered. The energy burst resulting from the interactions among twisted flux tubes turns out to be much stronger than the burst of one twisted flux tube which makes reconnection with untwisted field lines. Reconnection and burst-like energy release are repeated intermittently and the magnetic field topology returns to the initial state after several reconnections and energy bursts. These features are common and universal for all cases.

From these results, we can propose a new scenario of self-organization for an open system where energy is continuously supplied from outside. The initial stable state reaches an unstable state subject to a steady energy supply. Nonlinear development brings the system to a marginal (supersaturated) state which is a nonlinear bifurcation point, whereby reconnection is driven and the topology of the magnetic field is changed. Through this relaxation process, stored magnetic energy is rapidly release and a stable state, which is a local minimum energy state, is realized. Upon a continuous energy supply, the energyt accumulation and energy relaxation take place in an intermittent, burst-like fasion. Alternating a marginal state and a local energy minimum state, the system returns in the meantime to the initial state, which may be the global minimum energy state. The intermittency and recurrence in the relaxation processes are the common and key features that characterize the self-organization in the open system subject to a continuous energy supply.

論文の審査結果の要旨

閉じた系における不安定平衡な配位（高いエネルギー順位）からの自己組織化に対しては、これまでいくつかのシミュレーション研究が行われ、多くの知見が得られてきた。本論文では、対象を開いた系として、安定な配位に対して系内にエネルギーを連続的に注入することによって、磁束管の構造変換（自己組織化）が間欠的に起こり、何度かの局所平衡状態を経過して、再び元の安定平衡な磁場構造配位に回帰するということを示すとともに、これらの構造変換に際しての磁場エネルギー、運動エネルギー、熱エネルギーの相互間変換、及び、磁気ヘリシティの遷移の様子をシミュレーション研究によって、詳細に明らかにしている。更に、本論文の結論として、自己組織化の普遍的シナリオの提言を行っている。

本論文は、従来の研究の一般的スタイルである要素還元論的立場を離れ、系の織りなすところをあるがままに、しかし数値的には正確に捉え、「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、大きな価値がある。従って、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磁束管の構造形成という特定のモデルの研究成果にとどまらず、示された自己組織化の普遍的シナリオが、一般的な構造形成において何処まで適応できるかといった点においても、プラズマ物理学に限らず、他の広範な分野における研究に今後大きく貢献するものであると考えられる。

また、本論文では、シミュレーション研究において常につきまとう数値的誤差という危険性を徹底的に検討・排除することによって、エネルギー変換の詳細を時間を追って綿密に解明している。このことは、磁気流体におけるプラズマにおける自己組織化にともなうエネルギー変換の物理的意味とそのシナリオを明らかにしただけでなく、MHDシミュレーション研究における数値的信頼性の性格・扱い方をも明確に示しており、今後、他のMHDシミュレーション研究に対する貢献度も大きいものがあると考えられる。

審査委員全員が提出された博士論文内容に関し、論文内容、及び、プラズマ物理学、計算機シミュレーションに関連した質疑など、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、シミュレーション研究の方法論及びその結果に対して、出願者が自己組織化研究の現状を把握し、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、また、自己組織化の普遍性に対する考察の説明も審査委員を納得させるものであり、十分に独創的な研究であると判断される。

提出された英文論文から、英語文章力についても十分な実力を有していると認められる。

よって、審査委員会は試験に合格と判断し、また、平成７年２月２２日の数物科学研究科教授会において最終的に合格と決定された。