Computer Simulation of Complexity in Plasmas

Takaya Hayashi, Tetsuya Sato,
and the Complexity Simulation Group

National Institute for Fusion Science,
Oroshi, Toki 509-5292, Japan
e-mail: hayashi@nifs.ac.jp

Abstract

By making a comprehensive comparative study of many self-organizing phenomena occurring in magnetohydrodynamic and kinetic plasmas, we came up with a hypothetical grand view of self-organization. This assertion is confirmed by a recent computer simulation for a broader science field, specifically, the structure formation of short polymer chains, where the nature of the interaction is completely different from that of plasmas. It is found that the formation of the global orientational order proceeds stepwise.

I. Introduction

Self-organization is a generic process in nature, which describes spontaneous formation of ordered structure. Creation of orderliness is one of the central problems in the Science of Complexity. Self-organization may be typical of the nonlinear and nonequilibrium process which evolves in an open system, and develops independently of the governing interactions of its specific components. When we turn our eyes to plasmas, such as fusion plasmas and space plasmas, plasmas are always nonuniform, and open to environments, thus they are in a nonequilibrium state. To release the free energy, therefore, the system becomes unstable. Because of its nonlinearity the evolution becomes highly complex. In some situations, plasmas reveal transition processes, which may be called self-organization. In this sense, plasma is an exemplar of a medium governed by complexity, and Plasma Physics is potentially a Physics of Complexity.

One important direction in plasma physics research is to pursue plasma as "dynamic science", rather than a "static science". From traditional studies of quiescent and steady equilibrium structures in closed isolated systems, the frontiers are expanding to consider the dynamics of open, nonequilibrium systems. Computer simulation is powerful in understanding complicated dynamics. Exploring dynamic nonlinear evolutions in open, nonequilibrium systems exposed to environments, namely, complexity, is the mission of "simulation science". At our institute (National Institute for Fusion Science), we sets up a research strategy towards its exploration by developing an innovative simulation system which is called "Grand Man-Machine Interactive System for Simulation (MISSION)". The primary purpose of this paper is to extract a grand view of self-organization through an extensive computer simulations of plasmas.

We first hypothesize that self-organization is governed by three key elements;

① Existence of an open complex system,

② Existence of information (energy) source, and

③ Existence of entropy generation and expulsion processes.

It may be natural to consider that self-organization occurs in an open system where an information (or energy) exchange can take place with an external world. When new information is introduced into a system, the system reacts upon it. When the amount of introduced information exceeds a certain threshold, the reaction may become significant and the system may experience a sizable change in its structure or state, i.e., the onset of a structural instability. A new ordered structure will thereby be created. During this process of structural change, or, phase transition, some chaotic state will be realized in an intermediate stage and something superfluous, which may be called natural odds and ends (entropy), is to be produced. In creating a clear-cut new structure, therefore, the cleaning up, or disposal, of those odds and ends is an important function. In addition to these interactions with the external world, the most important element is the nonlinearity of the system whereby operations of creating an ordered structure are practically conducted.

With these three elements in mind, we have done numerous simulations to extract a unified scenario of how order is created. Based on results of simulations which we have executed for plasmas with various configurations and states, we came up with universal features in self-organization

(1) The temporal behavior of self-organization is highly dependent on the way of energy supply. More specifically, when activation energy (information) is continuously supplied from an external system a nonlinear system self-adaptively can experience intermittent order creation, wondering local maxima and minima of the potential energy in a rather irregular way: intermittent self-organization. In contrast, when energy is suddenly pumped up in a nonlinear system and no pumping is given thereafter, then the system relaxes stepwise into a stable ordered structure.

(2) While an order is being created, the rate of entropy production is maximized; law of maximum entropy production.

(3) Depending on whether produced entropy is expulsed from the system or not, the created order structure can be quantitatively different.

II. Intermittent self-organization

We first show cases when activation energy is continuously supplied from an external system. Let us pick up a simulation of a twisted flux tube as a first example [1]. Initially, uniform straight field lines are applied in the axial direction. The axial boundaries are not periodic but are the suppliers of a continuous energy flow. Specifically, at the boundaries a circular motion is steadily applied in a limited region at both ends with the opposite polarity to each other, so that the magnetic field lines keep twisting. The bundle of straight field lines are twisted and squeezed toward the center in the initial phase. As the twisting proceeds, the stored tension energy of the twisted bundle of field lines is released in terms of a knot-of-tension type of instability. The instability develops in such a way that the kinked part of the flux tube collides against untwisted field lines. As a consequence, reconnection is driven to take place and relaxes toward an interconnected structure (a local minimum energy state). As the twisting goes further, the flux tube linked with distant untwisted field lines reconnects with a companion flux tube to come back to the original straight topology, i.e., grand cycle. Interestingly, it has been observed that the open nonlinear system responses in an intermittent fashion to a continuous input of energy.

A next example of intermittent self-organization is dipole field generation in a rotating sphere, like the case of the dynamo mechanism in the earth. A magnetohydrodynamic simulation is performed in a rigidly rotating spherical shell [3]. The inner spherical surface is kept to a constant high temperature and the outer surface to a constant low temperature. The convection instability develops and creates a well-organized convection structure, more specifically, paired cyclon-anticyclon columns along the rotation axis which stand side by side in a circle. When a tiny magnetic fluctuation is imposed in the system, the fluctuation develops and creates a well-organized magnetic structure, as well as the convection columns, that is, the dipole-dominant magnetic structure. This is a system that energy is continuously supplied in the form of the heat flux through the inner boundary. Interestingly, when this simulation is continued for a long time scale, intermittent phenomenon takes place. Namely, the reversal in the polarity of the dipole moment occurs, much like the well-known behavior in the geo-dynamo.

III. Stepwise relaxation

In this section, we show cases of stepwise relaxation when energy is instantaneously pumped up to a high energy state (far-from-equilibrium) in a nonlinear system. Observed in Ref. 4 is the time evolution of the magnetic structure in a typical example of a magnetohydrodynamic self-organization. The final helical structure is the self-organized one [4]. In the evolutions of the magnetic helicity and energy, it is observed that the relaxation occurs in two steps for the magnetic energy but not for the magnetic helicity. The two-step relaxation reflects the fact that there was another equilibrium (unstable) state between the given initial state and the final minimum energy state. We emphasize here that each stepwise relaxation occurs in a time scale which is quite a fast process compared with the classical diffusion time.

Shown in Fig.1 is a simulation of structural formation of polymers [5], which is executed to see the universality of the stepwise relaxation in nonlinear systems. Both bond interaction and non-bond interaction in polymer chains are modeled in this simulation. It is clearly observed that the orientationally ordered structure at low temperature is formed starting from a random configuration corresponding to a high energy state. As the curve for time evolution of an index of the orderliness in Fig.1 shows, it should be noted that the ordered structure is formed stepwise although the property of the interactive force and thus nature of nonlinearity for this system are quite different from the case of plasma.

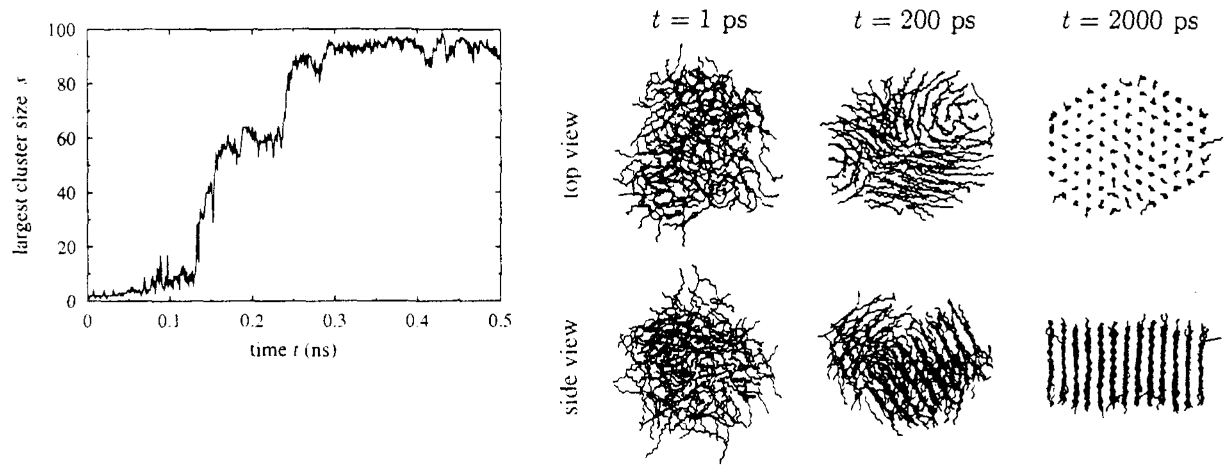

Fig. 1 Stepwise formation of orientational structure in short polymer chains.

IV. Entropy production and expulsion

In this section we examine, with particular attention, the dynamical relationship of the entropy production rate and expulsion function with creation of orderliness.

When we examine a typical example of the entropy production rate, namely, the volume-integrated ohmic heating, where intermittent self-organization takes place for the twisted flux tube stated above, one sees that the production rate repeats maximization at every sudden structural transition and minimization after transition. In the other example of the MHD self-organization stated in Sec.III where an energy (helicity) is instantaneously pumped into a system, the entropy production rate is maximized as the transition is taking place and minimized as it subsides. When the final minimum energy state is realized, the production rate almost vanishes. From these results, one can definitely confirm that whenever a new structure is being created the entropy production rate is anomalously increased, then minimized after the new structure is created.

Here, we shall attempt to look for what will happen when the produced entropy is filtered out. We take the ion acoustic double layer for this purpose [6]. What we have obtained is a remarkable and striking new self-organization phenomenon caused by filtering out the produced unnecessary entropy from the system. It is well known by particle simulation that weak ion acoustic double layer are generated in a one-dimensional collisionless plasma where electrons drift in ions. In the previous simulation, however, particles were regarded as periodic in a one-dimensional system. This periodic condition implies that the particles leaving from the downstream boundary enter into the system from the upstream boundary as they are and vice versa, no matter how seriously they are disturbed by the generation of ion acoustic double layers In other words, the disturbed information, or disorderliness, is retained in the system. A new particle simulation code is developed in which fresh particles continuously flow into the system from each boundary in place of dirty particles leaving the system. We can thus filter out the superfluous information (entropy), when produced. The result is really striking. A giant double layer is generated. Compared with the conventional ion acoustic double layer, the potential difference of which is of the order of one electron thermal energy, the potential amplitude of this giant double layer reaches a surprisingly large level, say, larger than ten times the thermal energy. This giant double layer has a much longer lifetime than that of the normal weak ion acoustic double layer and exhibits a recurrent generation.

The implication of this simulation is that if the system contains a proper filtering function of the superfluous disorderliness, then a well-organized structure can be realized and sustained for a long period.

V. Summary: scenario of self-organization

When a system gains energy, gradually or instantaneously, from an external world, beyond a threshold (marginal) point, an instability arises. The reaction of the system is to deform its own structure so that the deposited energy is stored as much as possible. When the supplied energy far exceeds the instability threshold (a supersaturated state), the instability develops sufficiently. The nonlinearity is enormously enlarged thereby and gives rise to a large deformation of the structure. The deformation progresses in such a way that the excessively deposited energy is released along the shortest path. In order to release it in the shortest path an anomalous dissipation, or an anomalous entropy production, must take place in one way or another. Simultaneously, the structure (topology) must be drastically changed, namely, a nonlinear bifurcation must take place.

These results and others have led us to the assertion that a natural open system in a far-from-equilibrium state tends to boost itself up to a bifurcation (phase transition) point, which then gives rise to an anomalously enhanced dissipation rate, or an anomalous entropy production rate, by whatever process it may be realized, whereby a well-organized orderliness is created.

References

1. H.Amo, T.Sato, and A.Kageyama, Phys. Rev. E 51, 3838 (1995).
2. H.Kitabata, T.Hayashi, T.Sato, and the Complexity Simulation Group, Phys. Soc. Jpn. 65, 3208 (1996).
3. A.Kageyama and T.Sato, Phys. Rev. E 55, 4617 (1997).
4. R.Horiuchi and T.Sato, Phys. Rev. Lett. 55, 211 (1985).
5. S.Fujiwara and T.Sato, J. Chem. Phys. 107, 613 (1997).
6. T.Sato, H.Takamaru, and the Complexity Simulation Group, Phys. Plasmas 2, 3609 (1995).
7. T.Sato and the Complexity Simulation Group, Phys. Plasmas 3, 2135 (1996).