ON L TO H-MODE TRANSITIONS OF THE TOKAMAK AND ENTROPY REDUCTION

by

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In an ideal case, it is assumed that the models for tokamak and stellarator plasma behaviour lead to the theory of invariant manifolds by Rastović [Chaos , Solitons & Fractals, 2007]. But , at the present state of knowledge, a more realistic concept for describing L to H transitions and edge localized modes is the reduction of entropy and appropriate methods.

Key words: transport equation, tokamak, anomalous diffusion, magnetic confinement, absorption

INTRODUCTION

In this paper, efforts were made to further the understanding and exploitation of the stochastic edge in tokamaks and L-H transitions [1]. Improvement in the use of edge stability models is necessary. Presently, the International Thermonuclear Experimental Reactor (ITER) includes plans for the stabilization of resistive wall modes, presumably using external coils. If we wish to opt for internal coils, key experimental results are needed to clearly show feedback stabilization below the critical rotation and a clear advantage of internal over external coils.

Last year, extremely good initial results were obtained with the suppression of edge localized modes (ELMs) with stochastic layers. It remains important to understand the impact of plasma shape and plasma profiles on the stability limit. More efforts are required for acquiring an in-depth understanding of both the poloidal flux transport and thermal transport.

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DESCRIPTION OF L TO H MODE TRANSITIONS

The divertor enables access to a new neutral beam injection (NBI), heated, high-density operating regime with improved confinement properties. The motion of the particle near the plasma edge may jump from L-mode to H-mode. The jumping phenomena in L-H mode transition lead to the change of energy in the motion of the particle near the plasma edge. The nature of anomalous transport was also investigated, using a transport model for stellarator W7-X in [2]. With stellarator W7-X, impurity accumulation, normally associated with ELM-free H-modes, is avoided. The results provide a promising basis for future experiments. A typical time series during ELMs is seen [3, 4]. The anomalously rapid loss of heat and particles from magnetically confined plasmas has been the subject of intensive research and is now widely behieved to be caused by fluctuations driven by plasma instabilities. Feedback control systems can, potentially, suppress some of these instabilities and reduce transport.

It is well established that detached divertor regimes offer a significant reduction in the divertor target plate incident heat flux. In a detached operation, the role of plasma recombination increases, hence neutral-neutral collisions in edge plasmas become more important. The non-uniformity of the turbulence results from edge effects.

The transition from L to H happens when the instability drive is large enough. Naturally, H is the local edge factor and does not necessarily give an overall confinement improvement. The components facing the plasma can potentially reach high temperatures. This may be avoided by the fusion power shutdown system that terminates plasma burn.

Quasi-Monte Carlo methods are developed by using smoothing and dimension reduction of the integration domain. The H-mode edge transport barrier is now routinely turned on and off. ELMs have both poloidal and toroidal structures and the most dramatic edge events seen in the plasma periphery are the ELMs. In Lagrangian models, the concentration of the quantity transported by a turbulent field is reconstructed from the trajectories of the individual particles affected by the flow. Given a general knowledge base about a population of particles, the problem of applying is considered that general knowledge to reason about whom we have only some partial and uncertain information. Maxent is introduced as an updating procedure appropriate to the sort of information involving expert systems.

Indeed, modern ergodic theory tells us that a sequence of measurements mimics with finite precision a truly random sequence and, therefore, these systems appear to be precisely those deterministically random systems required by the transport theory. A model with a zero Lyapunov exponent has been presented which, nevertheless, exhibits unbounded Gaussian diffusive behaviour. The results provide convincing evidence that linear mixing systems (*i. e.* with a zero Lyapunov exponent) obey the Fourier law.

Random walks on random graphs can exhibit anomalous behaviour and yet have well-defined and predictable properties [5]. Anomalous diffusion can result when steps of a random walk are not statistically independent. The original Fermi, Pasta, Ulam (FPU) report indicated the motivation and the procedure for the Monte Carlo method. Ergodic behaviour was studied with the aim of establishing, experimentally, the rate of approach to the equipartition of energy among various degrees of freedom of the system. Some scientist have found that counter-intuitive, non-equipartition of energy (non-thermalization) result for a non-linear system.

FRACTAL ASYMPTOTICS

The periodic orbit theory provides an effective approach to computing useful properties such as averages, Lyapunov exponents and dimensions, particularly when the fractal corresponds to a non-attracting set, so that direct simulation methods are harder to implement. Stochastically perturbed dynamical systems constitute a vast field, involving many methods other than the periodic orbit theory. Specifically, we are interested in conditions under which an unbounded memory can induce qualitative changes in the distribution of the position, as compared to the Markovian case with Gaussian distribution pertaining to large space and time scales. Hence, one has the standard Markovian random walk which, on large scales, converges to Brownian motion. A Markov decision process is studied, *i. e.* a controlled Markov process whose state process under a stationary policy is an ergodic Markov chain.

Toroidal and poloidal momentum confinement in neoclassical quasilinear theory in tokamaks and stellarators is under development. The theory is applied to explain the changing of the toroidal and poloidal flow direction after low mode to high mode (H-mode) transition observed in some experiments. Toroidal momentum confinement in tokamaks is most likely to be anomalous . This implies that a quantitative theory for the toroidal flow is difficult, if not impossible. Fortunately for H-mode, the radial electric field is predominately determined by the poloidal momentum equation or the parallel momentum equation. The poloidal momentum equation can be described fairly by the neoclassical theory [6, 7]. Harris's recurrence ensures that , from any initial state, every set of states dense enough can not only be reached with positive probability, but are hit infinitely often, with probability 1. Harris's recurrent chain admits an invariant measure. The study of the optimal control of queuing networks for a suitable limit controlled diffusion process is currently an active area of research [8].

To compute the connectivity quantities of interest, use must be made of an alghorithm that distinquishes the various clusters in the system and minimizes, to the utmost extent, the effect of the system's finite size. Results suggest that a statistical theory of high-dimensional attractors in terms of unstable periodic orbits (UPOs) might be possible even in the absence of hyperbolicity or of symbolic dynamics. As time t tends to infinity, the solution of Boltzmann equation tries to maximize the entropy $S(f)$ under the constraints given by the conservation laws, which means mass and kinetic energy. Since the maximizer is a Gaussian distribution, we expect the behaviour to become nearly Gaussian as t becomes large. Poincarre's recurrence theorem implies: With probability 1, all the particles will come back (almost) to their initial positions, after some time. There is no contradiction with Boltzmann's theory: it only shows that, after a very long time, Boltzmann's equation is not an accurate model. Keeping this in mind, a theoretical statement about the Boltzmann equation is scientifically satisfactory only if there is control over time series involved.

Self-similar fractal sets in Euclidean space are usually constructed by iteratively applying fixed contractive mappings (chosen randomly and independently at each step) to a given initial set. The fractional Fokker-Planck equation is introduced to model the anomalous diffusion. The asymptotic shape of its solution is a stretched Gaussian. The ergodic theorem for contractive Markov systems (CMS) provides an unifying framework of, so-called, "fractal" geometry. Important application allows an empirical calculation of the Kolmogorov-Sinai entropy of the generalized Markov shift associated with a given CMS, without explicitly knowing anything about its invariant measure [9].

It became clear much later that the boundaries of islands can strongly influence kinetics and transport and impose a new type of kinetics, fractional kinetics and non-Gaussian transport. The FPU-problem has led to non-ergodicity of real dynamics and its influence on statistics and transport. The non-linear systems have such a level of complexity that they should display random dynamics. In non-ergodic mixing, some zero measure sets cannot be neglected. The coordinates do not follow a regular diffusion pattern. They have very long "flights", also called Levy flights, that drastically change kinetic and transport properties. Essentially, the information contained in a measurement of all of the system's variables as a single time is reconstructed from measurements of a single variable at q different times. The number of delays q should be large enough to reproduce the dynamics of the system.

Fully developed chaotic system is considered for which the projected dynamics reduces to a Markov chain. The process generated by the deterministic dynamics on the phase space partition is now shown to be highly non-Markovian.

There is much experimental evidence that the heat flux to divertor plates or to limiters is very asymmetric. Hand in hand with quasi-axisymetry, come other tokamak features. Stellarator W7-AS will have a quasi-poloidal symmetry and a zero toroidal plasma current and will be able to repeat a discharge in a reliable and reproducible manner. Progress in the prediction of disruption via neural and fuzzy-neural techniques has been made. It has lead to improved stability and confinement properties. The aim is to construct magnetic fields which lead to a stabilizable stationary equilibrium, without causing disruption in the confinement process.

The Kolmogorov-Arnold-Moser (KAM) theorem: Phase spaces of Hamiltonian systems split up in various areas when coupling between the deegres of freedom are coupled in such a way that the equations become unintegrable. These areas are either:

– island shaped,
– unbroken layers (KAM tori), and
– chaotic.

This paper is concerned with the optimization of the chaos game algorithm when it is used to construct a fractal image generated by an iterated function system. At least one optimal set of probabilities for a chaos game exists.

The FPU-problem can be defined as the problem of energy equipartition among normal modes in a weakly, non-linear lattice, starting with the initial condition, far removed from the statistical equilibrium. The formation of the metastable state has recently been understood in a very satisfactory way within the soliton theory. Weakly chaotic systems are systems with mixed phase space, including anomalous (non-diffusive) transport and non-ergodicity The time scale for equipartition can be quite short. At the lowest Fourier mode, the FPU recurrences amount to a few procents of Poincarre's recurrences.

ANOMALOUS TRANSPORT

Based on the method of self-sustained turbulence, the anomalous transport coefficient is derived for various toroidal plasmas. L-mode confinements in tokamaks and stellarators are explained by means of magnetic geometry. The mechanism of confinement improvement is also discussed. Associated with the H-mode, bifurcation physics is described. The catastrophic event at the beta-limit is discussed, as well. Rescaled range-analysis techniques are used to investigate long-range dependence in plasma edge fluctuations. The tail of the autocorrelation function decays as a power law, suggesting that there is a superdiffusive component of the anomalous transport. The probability distribution of particle density at the edge of several magnetic fusion devices, including tokamaks and stellarators, is known to be strongly non-Gaussian. One approach to deriving the kinetic equations relies upon work which generalizes the ergodic theory. Is it really possible to show that the system has such a randomizing feature (in the light of the KAM theorem, for example)? The thermodynamic principles demand a world in which physical processes are asymmetric in time. The long-range dependence criterion tells us that the behaviour of the process after time t depends not only on the situation at time t, but also on the previous history of the process. A Brownian control problem that arises in queuing theory is formulated and solved.

A stable distribution is a family of distribution functions that, if random variables f and g each have distributions from that family, the random variable which is their sum will have a distribution of the same family. The normal (Gaussian) distribution is a special case of a stable distribution. It has the distinction of being the only one with a finite variance.

P. Levy determined the conditions for a family of distributions to be stable. These distributions are usually called Levy stable distributions. Unfortunately, the general form of Levy distributions is not available. What is available is their moment generating function. In particular, the global stochastic fluctuations of the systems differ from the normal Gaussian noise according to the time and size scales at which these fluctuations are considered. Levy flight and walks are stochastic processes which provide a framework for the description and analysis of anomalous random walks in physics. The characteristic of anomalous diffusion is usually based on the time evolution of a mean-squared displacement which corresponds to a non-Brownian behaviour in some cases. Due to the sticky barriers (formed by cantori), a particle trajectory may be trapped for a long time near the corresponding regular islands and may produce long indirectional flights with a constant velocity. This velocity is equal to the corresponding winding number of islands and leads to a superdiffusion behaviour.

Data from chaotic systems do not repeat the same time series of values. This means that a valid mathematical model will not be able to predict the values of a time series. The mean and the variance are not always a meaningful way to characterize data. The average depends on lenghts of time. Predictability of the time series is not necessarily a meaningful way to test the validity of mathematical models. For a long time, we thought that most data must have a normal distribution and therefore that the mean is meaningful. Much of nature is definitely not "normal". The attractor is the "real" thing , the invariant of the system. The time series of data from an experiment is not necessarily the "real" thing. The mean of a sample of data is called the sample mean. For data with fractal distribution of values, the means of those samples continue to either increase or decrease. There is no unique value that characterizes the data. The population mean is not defined. However, when the probabilistic distribution function (PDF) has a power law fractal form, the averages measured depend on the amount of data analyzed.

Fuzzy identification systems and fuzzy neural networks represent an alternative solution to the problem of predicting the time of disruption in tokamak machines. The use of the concept of fuzziness is also suggested because the transition of a discharge toward "disruptive behaviour" happend without appearing to be a continuity solution , *i. e.* by "soft" transitions. The aim of the procedure is to give a correct estimation of the time of disruption in order to enable the activatation of the control system. Most of the plasma disruptions in ASDEX-Upgrade happen in a plasma parameter range (poor L-mode confinement which is far away from the desired operational mode (H-mode, high beta). The new feedback controls of the neutron emission rate and the radiative power in the divertor have been performed in 1995 [10]. A simple feedback control model in which the divertor radiation power measured by a bolometer is used as a control parameter has been developed in JT-60U [11].

Diffusion in most plasma devices, particularly tokamaks, is higher than one would predict from understood causes. The observed typical diffusion is refered to as anomalous because it has not yet been explained. The statistical description in fully developed turbulence is often implicitly linked to a particular geometry for energy dissipation support. Kolmogorov's theory assumes a homogenous field for dissipation, the beta model uses the fractal description and, more recently, the multifractal approach has been proposed. In collaboration with Ben Carreras, George Zaslavsky has undertaken to apply sophisticated methods for analyzing edge fluctuation data from D-III tokamak in order to discover non-Gaussian processes which may have major effects on transport. The analysis hand the start of advanced data analysis of turbulence in tokamaks [12].

REDUCTION OF ENTROPY

A simple expression of the diffusion coefficient in terms of the Hausdorff dimension and the positive Lyapunov exponent of the chaotic model are derived. This leads to a new relationship between transport and chaos. Max Ent has now become a powerful tool in non-equilibrium statistical physics. Experiments need not be repeatable, but sometimes they are. Let us assume that successive repetitions are possible and that they happen to be independent . The joint distribution and the appropriate entropy are derived. The problem is not a failure of the Maximum entropy method, but a failure to include all the relevant information. For additional information, additional effort will be required to obtain the needed value of entropy.

A generalized, information-based, inversion procedure for the tomographic reconstruction of the soft X-ray emissivity of a hot fusion plasma is developed [13].

In the case of fully chaotic systems, the distribution of Poincarre recurrence times is an exponential whose decay rate is the Kolmogorov-Sinai entropy. In the case of sporadic randomness, resulting at long times in the Levy diffusion processes, the sensitivity to initial conditions is intially a power-lay, but it becomes exponential again in the long-time scale. The non-Markovian character of the dynamics is expressed in the fact that the evolution equation is different for each initial position.

Let X be an operator stable Levy process with exponent B, where B is an invertible linear operator. The Hausdorff dimension and the packing dimension are determined in terms of the real parts of the eigenvalues of B. Many authors have investigated the Hausdorff dimension, Hausdorff measure, packing dimension and packing measure of various random sets generated by the Levy processes. Operator stable Levy processes are scaling limits of random walks.

INFORMATION-THEORETIC APPROACH TO THE STUDY OF CONTROL SYSTEMS

An information-theoretic framework is proposed for analysing control systems based on the close relationship of controllers to communication channels. A communication chanel takes an input state and transforms it into an output state. A controller, similarly, takes the initial state of a system to be controlled and transforms it into a target state. The idea of reducing the entropy of a system using information gathered from estimating its state is not novel by itself. The vertices of graphs correspond to random variables representing the state of a (classical) system; the arrows give the probabilistic dependencies among the random variables according to the general decomposition. The effect of the subdynamics available to a controller is characterized by the entropy of the initial state X. Each actuation subdynamics represented by the control graph can be characterized by a conditional open-loop entropy reduction.

The approach of symbolic analysis of time series is suggested in cases when data are characterized by a low degree of precision, *i. e.*, when the available information is esentially qualitative. This article extends the scope of the application of symbolic analysis to control design. For that purpose, the input/output time series is first analysed to derive a model in the form of a controlled Markov chain, which is then used to formulate and solve a control problem. The goal of the control policy can only be qualitative. In this sense, a resonable goal is that of reducing the range of the variability of the output (chaos confinement). Symbolic dynamics is a method for studying non-linear, discrete-time systems (maps) by the coding of the trajectory with a sequence of symbols taken from a finite set. The use of symbolic methods for estimation of entropy and fractal dimension is possible. The quality of a model can be evaluated by its predictive ability. A quantitative assesment of the predictive ability can be obtained by means of the Shannon entropy. Control policies mapping a symbolic information into symbolic control are considered. Fixed point behaviour is when for the constant input, the output is constant. Entropy reduction means that the output probability will be concentrated in the target set A, while it will be almost zero outside of the set A.

We have shown, in detail, how the method of time series analysis, such as dimension and entropy estimates, support the idea that fast, low-dimensional chaos can be modelled properly by noise. In the situation we are interested in, only a small, definitely finite number of fast degrees of freedom will be responsible for the generation of stochasticity. We require our fast variables to be chaotic themselves. Hence, they possess positive, but finite Kolmogorov-Sinai (KS) entropy, which, under a suitable rescaling of time, can diverge. The KS entropy of a deterministic system can only be seen at sufficiently small scales. Dynamical entropies, hence, contain non-trivial information for both deterministic and stochastic data, since they can possess a rich structure as a function of the length scale. The identification of unstable periodic orbits in inter-edge-localized-mode intervals in JT-60U is based on their recurrence properties and the so-called fixed point transform and they can be stabilized by small perturbations. The inter-ELM interval time series [14, 15] can be extracted from the emission signal.

DESCRIPTION OF THE L TO H TRANSITION

Auxiliary heated tokamak experiments in the L-mode confinement regime reveal a degradation of confinement with increasing power. The H-mode confinement regime is characterized by an increased factor of 2 to 3 in the confinement time and a decrease in plasma edge fluctuations. The transition from the L to H-mode is rapid (less than 2 ms) and happens for input powers above a threshold. The transition seems to be independent of the heating method and magnetic field geometry. Experimentally, it has not yet been possible to determine the causal relation of the onset of the L to H transition. An even higher confinement mode, the very high (VH) mode, was recently discovered in the D-III tokamak. It is quite likely that the VH-mode regime is a natural extension of the L to H transition. Even the best existing pseudorandom number generators can yield incorrect results due to the "unvoidable correlations that appear between the generated values". On the other hand, there is a great interest in random dynamical systems. The forecasting methods are very effective in distinquishing chaos from random time series. The motivation for our work is: how to produce truly random numbers which are necessary in different physical calculations such as the Monte Carlo method. In fact, the first–return map is multivalued.

Now, the problem is to describe the simulation of non-stationary Markov chains. The next theorem holds.

Theorem: let us have plasma behaviour which is described by the KAM theorem. Then, it can be simulated as follows:

(a) by a generalized fixed point method in the deterministic case (H-mode), and

(b) by the maximum entropy principle in the stochastic case (L-H transitions and ELMs).

Proof:

(a) The proof is given in [16]. It all follows according to the contraction mappings principle with fuzzy logic controllers.

(b) Let X be a recurrent, non-stationary strategy countable Markov process with several equilibriums. Then it can be approximately simulated by an infinite fuzzy logic controller based on Bayesian learning rules. The KS entropy is defined. The distribution functions are considered as unknown variables still to be determined. This requires a maximum value of KS entropy under some given contraints. The maximization, under the constraints, can be performed by the use of Lagrange multipliers under reduction of entropy [17, 18].

Our understanding is that it may also be necessary to stabilize or control certain magneto-hydrodinamics (MHD) instabilities to avoid disruption. The ITER plasma must be termined in a controlled manner in which first the fusion burn, and then the plasma current, are shut down without disruption.

It has been possible to "control" or optimize the plasma operational regime so as to obtain operation modes with enhanced energy confinement relative to that obtainable in the standard auxiliary-heated L-mode regime. This operational regime – control capability combined with the implementation of closed-loop feedback – has allowed high plasma energies to be obtained more regularly and reproducibly.

In this regard, the increasingly long characteristic times scales have helped in the implementation of feedback control concepts that make the attainment of such stationary plasmas possible. The key physics elements for real-time plasma control are a set of suitable plasma diagnostics and control actuators. Improved understanding and modelling and the availability of control methods (actuators) can result in better control and optimization of plasma performance.

CONCLUSION

The distribution of Poincarre's recurrences will play a crucial role. In the case of dynamical chaos with fairly good mixing properties, one can expect a Poissonian law. For different types of systems, the anomalous kinetics was explained by the presence of the so-called Levy flights. It has been proved that for compact phase space and ergodic motion with non-zero measure, the mean recurrence time is finite.There is an exact self-similar set of islands that generates enormously long flights.

Computer simulation of many important complex physical systems has reached a plateau because most conventional techniques are ill equipped to deal with the multi-scale nature of such systems. Several transport regimes have been found, featuring both subdiffusion, corresponding to Levy flights in the stochastic layer.

A statistical treatment of the turbulent flow continues to pose problems for theorists. One suggestion invokes an analogy with equilibrium phase transition. The distributions have non-Gaussian tails that characterize large-amplitude fluctuations. The Reynolds number Re characterizes the complexity of the fluid motion; it is defined as the ratio of the non-linear to dissipative forces. The probability density function for the fluctuations has been measured for different Reynolds numbers. Hence, any system of a finite Reynolds number can be considered as containing a finite number of degrees of freedom. Given that many scales are important, the simplest scenario is a self-similar one. Systems with the same critical behaviour are grouped together in "niversal classes". The velocity distribution of the fractal turbulence is shown to be stable distribution. The diffusion process of particles in the turbulence can be approximated by the Levy process [19, 20].

It has been ilustrated that in the case of choosing parameters, the normalized radial electric field near the plasma edge in a tokamak is stable. A large magnetic proton recoil spectrometer measures the 14 MeV neutrons from the fusion plasma and is a valuable tool for plasma diagnosis. From the analysis of the results, we are able to say that the onset of the disruption is predictable within a practically interesting time interval [21]. The mechanism of the L to H-mode in a tokamak is an important and difficult problem within the tokamak concept. Local and global bifurcations of the transport equation for the L to H-mode transition near the plasma edge in a tokamak are investigated by using the theory of non-linear dynamics [22].

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Данило РАСТОВИЋ

О ПРЕЛАЗИМА ТОКАМАКА СА L-ОБЛИКА НА H-ОБЛИК И О РЕДУКЦИЈИ ЕНТРОПИЈЕ

Код унапређених фузионих реактора, у идеалним околностима, може се системом управљања с магнетним одржавањем кретање релевантних честица у линеаризованом случају учинити експоненцијално стабилизујућим. Међутим, због рада у реалним условима, очекује се да дизајн бланкета и дивертора с механизмима апсорпције значајно утиче на режим аномалне дифузије и пратеће појаве зрачења, те на хамилтонијан транспорта у редукованом потпростору.

Кључне речи: транспортна једначина, токамак, аномална дифузија, магнетно одржавање, апсорпција