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A Possibility for a Self-Consistent Treatment of Transport Processes in a Turbulent Plasma

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A POSSIBILITY FOR A SELF-CONSISTENT TREATMENT OF TRANSPORT PROCESSES IN A TURBULENT PLASMA

by

J. P. Mondt

ABSTRACT

All commonly used models of plasma dynamics share a common flaw in their a priori validity. In particular, a solid foundation of plasma modelling on microscopic dynamics, as exists for moderately dilute gases, is obscured because of the difficulties inherent in the treatment of the potentially very important interplay between plasma waves and collisional processes. The present report briefly discusses the nature of these difficulties and presents a possible approach towards the establishment of a plasma theory founded on the microscopic particle dynamics. The essence of this approach is the realization that only discrete particle interactions can create correlations. These therefore come into being on different spatial scales depending on their cluster number, after which collective effects magnify them analogous to the growth of initial perturbations in an unstable system. Truncation of the Born-Bogolyubov-Green-Kirkwood-Yvon ('BBGKY') hierarchy thereby becomes a possibility through the introduction of a small parameter in initial conditions although the dynamical system in itself does not contain a uniformly small parameter.

INTRODUCTION

The central problem in any transport theory is the determination of its correlation functions (i.e., functions describing the relation between the interaction among particles and their statistical distribution in phase

space).¹ For example, the spectral energy density, the free energy density and the collision integral all are functionals of these correlation functions.

In the case of a turbulent plasma, there exists no satisfactory derivation of the size and functional form of correlation functions that is based on the fundamental equations of motion, the Klimontovich² equation, or, in the case of a Hamiltonian system, the BBGKY hierarchy equations,³ formally equivalent with Liouville's equation.

The present research proposition consists of an attempt to remedy this situation, thereby providing a microscopic foundation for the theory of transport processes in a turbulent plasma.

WEAK TURBULENCE

In the case of a weakly turbulent plasma (i.e., the energy density associated with the turbulent field fluctuations is much less than the thermal particle energy density), the shortcoming of the usual treatment consists in the neglect of particle-particle interactions in the derivation of the so-called "weak-turbulence kinetic equations."⁴ It is common practice to defend this neglect by referring to the smallness of the degree of collisionality, measured by means of classical estimates for relaxation times and the range of the ensemble-averaged particle potential. But as is well-known,⁵ these classical estimates do not hold in the presence of turbulent fluctuations. In fact, they cannot be trusted even in order of magnitude, since the presence of unstable roots of the dispersion equation, derived from a collisionless theory, translates into exponential growth and non-Markovian behavior of the collision term that had been neglected from the outset.

Conclusively, what is needed in the theory of a weakly turbulent plasma is a self-consistent treatment of collisions and instabilities, i.e., a treatment that takes into account the effects of instabilities on collisional interactions before making any estimates of the effects of collisions on instabilities; thereby verifying whether the assumption of weak turbulence is preserved during any reasonable interval of time.

STRONG TURBULENCE

In the case of a strongly turbulent plasma, transport theory so far has only been developed on the basis of model equations, not based on the fundamental equations of motion pertinent to a many particle system.⁶ This is due to the absence of any small parameter in the fundamental equations, except for the degree of collisionality that has been put equal to zero from the outset.

However, only interactions can create correlations in a closed system. In passing it is noted that this circumstance is the reason for assuming vanishing initial correlations.⁷ Furthermore, of all the different types of interaction (wave-wave, particle-wave and particle-particle), only the particle-particle interactions constitute a true source of correlations. The only effect of the other types of interaction is to increase their amplitude in a way analogous to the increase in amplitude of a disturbance due to an instability.⁸

Consequently, the neglect of collisions in determining the size and functional form of correlations in a strongly turbulent plasma is not justified no matter how small the degree of collisionality. Rather, a boundary layer analysis in the time variable is needed, such that, during the short time interval following the initial state, collisions are dominant. After this time interval, collisional effects could tentatively be neglected, depending on the exact properties of the system, and the correlation functions from then on are assumed to be subject mainly to wave-wave and wave-particle interactions. The mere fact that collisions constitute the source of correlations implies that their effect on them must exceed all other effects during a short time interval in which such correlations are created. Not only do they have to be taken into account: the fact that they are known to shape the different s-body correlations differently depending on the value of the cluster numbers, may very well imply sufficient discrimination between these various correlations to justify truncation of the BBGKY hierarchy. (Such a justification has recently been found for the case of a quiescent plasma.⁹) Thereby one could arrive at a kinetic description of the properties of a strongly turbulent plasma, despite the absence of any small parameter in the infinite set of hierarchy equations.

OUTLINE OF THE REQUIRED RESEARCH PROGRAM

First it would have to be investigated under what conditions (if any) the effects of instabilities on collisions preclude a collisionless description of transport processes in a weakly turbulent plasma. If collisions could be consistently neglected, then the commonly adopted⁸ ordering of the different s-body irreducible correlations should be correct. Therefore, the three-body irreducible correlation could be neglected in the second hierarchy equation, resulting in a closed set of equations for the one-body distribution and the binary correlation. These equations could conceivably be solved as they were in the case of a quiescent plasma, using a newly developed perturbation approach⁹. If the solution of these equations would show that collisions are important for the evolution of the one-body distribution function, then the first assumption made in the reasoning described above clearly must be incorrect. In that case, the relative orders of magnitude of the different correlation functions cannot be prescribed in an a priori manner; rather, they must be determined by the way they are built by collisions, as they were in the case of a quiescent plasma.⁹ In no way does one then still employ the assumption that the turbulence is weak.

Conclusively, the first step in this research would either: (1) Justify confidence in the assumption that collisional effects can be neglected on the evolution of correlation functions once these functions are significantly influenced by wave-wave and wave-particle interactions; or (2) Provide us with a drastically modified version of kinetic theory of a turbulent plasma, in which collisional effects have been properly taken into account.

In the first case, the boundary layer analysis of the evolution of correlations in the case of a strongly turbulent plasma could be simplified in a first attempt by neglecting such collisional effects on the evolution of correlations after the initial small period of time during which collisional effects are necessarily dominating. As already mentioned, in the second case, the analysis of collisional effects on transport in a turbulent plasma does not depend in any essential way on the assumption of weak turbulence.

For simplicity, considerations will at first be restricted to electrostatic turbulence in an electron plasma, where the ions constitute a continuous, uniform background of positive charge. Appropriate generalization

of the nonlinear hybrid-kinetic equations¹⁰ can be contemplated as a straightforward method of describing fully electromagnetic turbulence.

METHOD OF APPROACH

Recently, an accurate approximation for the solution of the BBGKY hierarchy equations was obtained for the case of a quiescent plasma.⁹ The method was based on the observation that two widely distinct spatial scales exist in the system, one associated with strong collisions, the other with weak collisions. The absence of analytic behavior of the one-body distribution function as a function of the plasma parameter, as well as the impossibility of any spatially uniform perturbation approach required construction of a new perturbation approach. Its success was mainly based on certain scaling properties of operators in the BBGKY hierarchy equations. Since these properties are independent of the assumption of stability, there is sufficient reason to attempt a similar analysis for the case of a turbulent plasma.

RELEVANCE

As a rule, rather than as an exception, plasma is in a turbulent state. This holds for laboratory plasmas, such as present and thermonuclear generations of tokamaks,¹¹ reversed field pinches¹² and stellarators¹³, as well as astrophysical plasmas, such as the solar wind.¹⁴ Without a microscopic foundation of the theory of plasma turbulence it will remain impossible to make any quantitative predictions about this phenomenon, nor will there be any true understanding of it within the framework of physics.

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