TURBULENCE AND QUASI-COHERENT STRUCTURES IN FLUIDS AND SPACE PLASMAS

Project No.: 2-CEX 06-11-47 / 25.07.2006
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The project is devoted to the development of a new approach to the problem of generation of coherent structures in fluid and plasma turbulence, based on concepts and methods of field theory, statistical physics and rigorous mathematical constraints. These new theoretical methods were applied to several concrete physical systems of fluids and space plasmas that imply turbulence and asymptotic stationary states. The aim is to obtain quantitative description and analytical predictions of the properties of ordered states of fluids and plasmas that are relevant for experiments, observations and numerical simulations. The research subjects proposed in this Project are theoretical, fundamental and interdisciplinary, with significantly many applications in the atmospheric science, gasdynamics, space plasmas and thermonuclear fusion. Three classes of problems related with basic aspects of turbulence, coherent and quasi-coherent structures were analysed and the following results were obtained.

1) Coherent structures generated from relaxation of turbulent states of two-dimensional fluids

We have developed an original field-theoretical model for the description of the quasi-coherent stationary states of two-dimensional fluids, like the planetary atmosphere, the magnetically confined plasma, etc. We have based our theory on the large number of experimental and numerical studies that have shown that the two-dimensional fluids and plasmas exhibit an intrinsic trend to organization. Our theory applies equally to tropical cyclones, to large scale flows in tokamak plasma and to crystals of vortices in non-neutral plasmas, all being characterized by an intrinsic length (Rossby radius, Larmor radius, etc.). We have shown[1] that the stationary states attained at late times in the evolution of such fluids are described by the equation

$$\Delta\psi + (1/(2p^2)) \sinh\psi \, (\cosh\psi - p) = 0. \qquad (1)$$

Here ψ is the stream function and p is a positive constant. This equation has been derived within a field-theoretical formulation of the model of interacting point-like vortices and reveals that the asymptotic state of organization of the physical vorticity in fluids and plasmas is identical to states of self-duality of classical field theory of matter interacting with a gauge field. The Lagrangian density consists of a kinetic part with covariant derivatives, the Chern-Simons term and a self-interaction of the scalar field, all fields taking values in the SU(2) algebra. Consistent with the physical model from which it is derived, this equation describes the states of fluids/plasmas characterized by the presence of a background of vorticity (a condensate of vorticity) and a finite intrinsic length (or a velocity of propagation of perturbation, like the gravity wave speed or the sonic speed).
The numerical solutions of this differential equation for different physical systems have provided structures that are very close to the observed ones: plasma vortices, atmospheric vortices, non-neutral plasma vortex crystals, current sheets.

2) Turbulence from the prospect of some gasdynamic interactions

C*oherent structures* are identified for modeling the gasdynamic turbulence. Regular interactions of wave-wave type determine such structures. A degeneracy could be possible in the

[1] F. Spineanu, M. Vlad, **Physical Review Letters 94** (2005) 235003.

multidimensional theory of these interactions. Finding an *admissibility criterion* [= nondegeneracy criterion] to select a nondegenerate solution appears to be important. We have described the *nature* of such a criterion and the nature of the nondegeneracy. We have analyzed the dependence of the structure of a regular interaction of a wave-wave type on the type of mathematical approach used ["algebraic", "differential", etc.]. The algebraic and the differential approaches were studied for two types of gasdynamic interactions: isentropic and anisentropic. We have demonstrated that the two approaches are equivalent in the first case and that the second case the differential approach is essential. We have found atypical gasdynamical structures.

We have obtained an invariant formulation of weak solutions of the Burgers-Hopf equation and we have associated the condition of entropic admissibility with a concept of weighting on the variety of characteristics.

3) Stochastic advection of particles and fields

The advection of particles in 2 and 3-dimensional stochastic magnetic fields was studied by developing an original semi-analytical method that applies both for the drift approximation and for the stochastic motion produced by the Lorentz force. Two nonlinear processes that strongly influence the transport were identified: the formation of stochastic magnetic islands and of stochastic magnetic mirrors. These two types of magnetic structures can produce the trapping of the trajectories determining trajectory structures. They interact leading to a complex dependence of the diffusion coefficients on the parameters. The results were applied to the problem of transport of charged particles in the solar wind.

We have determined the statistics of trajectories in electrostatic plasma turbulence and we have shown that quasi-coherence, trajectory structures and memory effects appear in the nonlinear regime characterized by large Kubo numbers. These trajectory structures strongly influence the evolution of passive fields and are related to the evolution of 2-dimensional plasma turbulence toward large scales (inverse cascade of the energy).

These results are presented in the 10 papers listed below and in 16 communications at international conferences (including 7 invited papers). A monograph concerning the topic 1 of the project was prepared [11]. The dissemination of the results was also done in 10 invited seminaries at prestigious scientific centers and as invited professors at Université de Provence, Marseille (M. Vlad for 6 months and F. Spineanu for 2 months). A weekly scientific seminary was organized at the Institute of Mathematics “Simion Stoilow” of the Romanian Academy during the whole period of this project.

1. F. Spineanu, M. Vlad, *Relationships between the main parameters of the stationary two-dimensional vortical flows in planetary atmosphere*, **Geophycical and Astrophysical Fluid Dynamics** (2008), in print
2. F. Spineanu, M. Vlad, *Zero-curvature formulation of asymptotic ordered flows of the Euler fluid*, **Romanian Reports in Physics** (2008), in print.
3. L.F. Dinu, *Multidimensional wave-wave regular interactions and genuine nonlinearity: some remarks*, **Preprint Series of Newton Institute for Mathematical Sciences**, Cambridge, UK, No.29 (2006).
4. L.F. Dinu and Marina I. Dinu, *Nondegeneracy: from the prospect of wave-wave regular interactions of a gasdynamic type*, **Preprint Series of Newton Institute for Mathematical Sciences**, Cambridge, UK (2007).
5. L.F. Dinu and Marina I. Dinu, *A class of exact solutions of the system of isentropic two-dimensional gas dynamics*, **Proceedings of Romanian Academy**, Series A, volumul **8**(2007), No. 1, pp.1-8.
6. L.F. Dinu, M.I. Dinu, *Nondegeneracy: from the prospect of wave-wave regular interactions of a gasdynamic type*, **Proceedings of Waves 2007**, p. 461, published by Department of Mathematics, University of Reading, ISBN: 0 704998 80 7.
7. L.F. Dinu, M.I. Dinu, *Two prospects of a regular nondegeneracy: details of a parallel*, **Proceedings on Applied Mathematics and Mechanics** (**PAMM**) vol. 7 (editata la Wiley InterScience).
8. M. Vlad, F. Spineanu, S. Benkadda, *Turbulent pinch in non-homogeneous confining magnetic field*, **Plasma Physics Controlled Fusion 50** (2008) 065007.
9. M. Vlad, F. Spineanu, *Nonlinear effects in strong turbulence in magnetically confined plasmas*, **Romanian Reports in Physics** (2008), in print.
10. M. Vlad, F. Spineanu, *Trajectort vortical structures and transport in turbulent fluids*, **Geophysical and Astrophysical Fluids Dynamics** (2008), accepted.
11. F. Spineanu, *“Field theoretical methods in fluid and plasma theory”*, Lecture Notes, 165 pages, http://florin.spineanu.free.fr/professional/lectures/lectures.htm.