Turbulence

Thursday, Sept. 3: 11:00 – 13:00

Session 3: MPI Lecture Hall

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Chaotic motion of light particles in an unsteady three dimensional vortex: experiment and simulation

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We simulate the motion of a small rigid sphere, lighter than the fluid in a model flow. The model flow is a rotating, three dimensional and periodically time dependent (a vortex).

The motivation of this work is an experiment. In the experiment a rotating magnetic stirrer generates a vortrex in a cylindrical container [1]. The core of the flow is able to keep a light particle near the axis moving up and down. Experiment shows that the smoothed out hydrodynamics of the flow is periodic but the motion of the particle is highly non-periodic.

Our model is a generalization of the Burgers vortex and describes the flow around the axis. The equations of motion of the particle are a modified semi-empirical Maxey-Riley equations.

The dynamical mechanism underlying the particle's chaotic-like motion is the coexistence of a fixed point attractor and a limit cycle about the vortex axis in the time-independent flow. Time dependence might combine these regular attractors into a single chaotic attractor.

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Size distributions of inertial particles in aggregation-fragmentation systems

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The dynamics of inertial particles in fluid flows has been subject of increasing interest in several disciplines, from dynamical systems to atmospheric science and turbulence [1]. Almost all the works have been devoted to the pure advective dynamics of inertial particles. Typically one assumes a dilute regime and fully neglects the collisions. To our knowledge, only very recent works have addressed effects of collisions on the dynamics of inertial particles. In [2] and [3], we have reported our first results on the dynamics of spherical inertial particles aggregating upon collisions and fragmenting under certain conditions. Our motivation lies primarily on natural phenomena such as the formation of cloud droplets, sediments in lakes and rivers, and marine aggregates in the ocean. Aggregation relates to the collisional growth, while fragmentation can be of two possible origins. First, particles break up if their size exceeds a certain maximum size. This is motivated by the hydrodynamical instability of large water drops settling under gravity. Second, particles fragment if the shear forces due to the fluid flow are sufficiently large. This mechanism has been reported to be the dominant one in the case of marine aggregates.

In most previous works the particles were considered to be spheres with a specific density. While this seems to be a good approximation for example in the case of raindrops, in many other cases, for example for marine aggregates, this is only a crude approximation. The non-spherical structure of particles can have a great influence on particle dynamics as well as aggregation and fragmentation processes. In the context of a mean field approach, a non-spherical particle structure has been incorporated in the past, e.g. by Kranenburg [4]. However, so far there are very few attempts to treat this problem for inertial particles in a flow. Wilkinson et al. [5] used a model for non-spherical particles in an aggregation model for dust particles during planet formation. We expand the consideration of spherical particles to model aggregates that have a fractal structure. We characterize this by a fractal dimension, which leads to a modification of the radii and effective densities.

We present results for the dynamics of a system formed by inertial particles undergoing aggregation and fragmentation, both with and without a fractal structure, and with the particles suspended in a number of different flows. Our main focus is the study of the size distributions of particles which evolve in the long-term limit. While most previous studies emphasize the role of aggregation probabilities, our results show that this is more relevant for transient effects, for example the initiation of rain showers in clouds. In situations where a steady state is of interest, fragmentation will be the most relevant process.

The size distribution of aggregates as well as the mean average size in the steady state depends on the type of fragmentation mechanism taking place. For fragmentation occurring under sufficiently large shear, the distributions typically decay exponentially fast beyond a certain aggregate size. The average size of aggregates is determined mainly by the fragmentation process. We derive a scaling relation for the average size and for the strength of the fluctuations of the average size in the steady state as a function of the aggregate strength. We give heuristic arguments how the average size of coagulates for long times depends on the critical stable size of aggregates, determined by the fragmentation mechanism and possibly fluid shear.

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Some recent results on Complex Plasma research under microgravity condition

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"Complex" plasmas consists of ions, electrons and highly charged micro particles and neutral gas. The name was originally chosen in analogy to "complex liquids" — which defines the class of soft matter systems that exist in the liquid form. In general soft matter is considered as a mixture of "supramolecular" and "molecular" components and considering these properties it is shown that complex plasmas represent that state where the "molecular" components (electrons and ions) is gaseous, whereas "supramolecular" component (dust particles) can form solid, liquid and gaseous states depending on the relative strengths between interparticle interaction and kinetic energy, in an analogous way to regular matter. In the laboratory, the microparticles are easily observable and the characteristic time scale (as given by e.g. the dust plasma frequency) is much longer than in "normal" electron-ion plasma. Furthermore, the rate of momentum/energy exchange between microparticles can substantially exceed the damping rate due to neutral gas friction (undamped particle dynamics), providing a direct analogy to regular liquids and solids in terms of the internal atomistic dynamics. This allows us to use complex plasma as an ideal model system to investigate many fundamental processes (phase transition, transport, wave phenomena etc.) at the most fundamental kinetic level.

In experiments on earth the microparticles are usually suspended against gravity in strong electric fields which creates asymmetries, stresses and pseudo-equilibrium states with sufficient free energy to readily become unstable. Under microgravity conditions the microparticles move into the bulk of the plasma and investigations of the three dimensional strongly coupled plasma under substantially stress-free conditions are possible . To enable such studies, the 'PKE-Nefedov' laboratory, a German-Russian cooperation project, was launched and installed on the ISS. The first basic experiments were performed in March 2001. The next generation plasma lab 'PK-3 Plus' was sent to ISS in december, 2005 and is currently operating there. These laboratories investigate mainly the properties of liquid and crystalline plasmas in a capacitively coupled rf discharge chamber. Some features of complex plasmas that have been observed under microgravity conditions at the (individual particle) kinetic level are: a microparticle free "void" in the centre of the system with a sharp boundary, demixing of complex plasma clouds formed by microparticles of different sizes, crystalline structures, torus- shaped vortices, coalescence of "liquid" complex plasma drops, waves, string fluid etc.

It is also very important to understand the nature of dust dynamics in presence/absence of plasma since it directly correlates the fundamental properties of dust-plasma interaction, such as charging-decharging, force balance, etc. After switching off plasma, some unusual properties are observed: dust cloud forms symmetric shock-like structures, dust cloud explosion, inter-penetrating particle flows etc. The focus of this paper is to present the recent analysis of the shock formation, decharging effects, dust dynamics in complex plasma just after the plasma is switched off in different missions under microgravity condition.

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Invariants of the velocity gradient tensor in turbulent flows

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The velocity gradient tensor $A_{ij} = \partial_j u_i$ can be used to characterize the fine scale motion of a turbulent flow. For example the local topology of the flow is determined by the rate of strain tensor and the rate of rotation tensor, which are the symmetric and asymmetric parts of A_{ij} . We study A_{ij} along Lagrangian trajectories in homogeneous, isotropic and stationary turbulence. Due to the isotropy the pdf of A_{ij} is a function of the invariants of this tensor. A detailed analysis of the statistics of these invariants will be presented. We estimate the drift-field of these invariants and examine the fluctuations of the forces (which determine the evolution of the invariants) around the mean drift-field. It turns out that these fluctuations are as long correlated as the forces it self.

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Collisions of particles suspended in turbulent flows

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Suspensions of small particles in a fluid ('aerosols') are ubiquitous in the natural world and in technology. Such systems may be unstable due to collisions of the suspended particles giving rise to aggregation or to chemical reaction. These collision processes are fundamental to understanding the formation of raindrops from clouds. It is an empirical fact that turbulence has a significant effect on such collision processes (determining their rate as well as the outcome of a collsion: fragmentation or coalescence). This contribution summarises our recent results on collision processes in turbulent aerosols [1]. Earlier results [2-4] are briefly summarised.

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An Investigation of the Dynamics at the Boundary between Laminar and Turbulent Pipe Flow

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The boundary between the laminar and the turbulent state is investigated in experiments in pipe flow. Stereoscopic and tomographic particle image velocimetry (PIV) are applied to visualize localized turbulent structures (puffs and slugs). These measurement techniques allow to spatially and temporally fully resolve velocity fields in a cross-section or in a volume of about 4 pipe diameters in length. The observed coherent structures are then compared to lower branch travelling wave solutions and edge states known from numerical simulations.

In the transitional regime turbulence in pipe flow appears in localized patches, so-called puffs, which have a fixed length and travel downstream at a constant speed. It has been demonstrated in recent studies that these puffs have a finite lifetime and that their decay is a memoryless process [1, 2]. Generally this behaviour is consistent with the assumption that the turbulent state forms a chaotic saddle in phase space. The present study focuses on the dynamical behaviour during the collapse of turbulence in an attempt to categorize transient structures at the basin boundary between the laminar and the turbulent state.

The experiments are carried out in a 12m long pipe which has an inner diameter of $D = 30mm$ and the working fluid is water. A four camera high speed PIV system is used to measure the velocity field either in a small volume (tomographic PIV) or in two cross-sectional planes (stereoscopic PIV) several diameters apart.
Three different experimental procedures are applied to investigate coherent structures(Figure 1.) that occur during the decay of turbulence. Firstly the naturally occurring sudden collapse of turbulent puffs is monitored. Of particular interest here is that even after characteristic features of the turbulent puff (like the energetic trailing edge) are lost, coherent structures persist. In a second set of experiments turbulence was established at Re=3000 and subsequently the Reynolds number was suddenly reduced. Thirdly the growth of perturbations is studied and again the focus is on the transient occurrence of coherent structures during the growth of the disturbance.

Overall this study aims to make a connection between experiments and previous numerical studies reporting observations of lower branch travelling wave solutions and edge states on the laminar turbulent boundary [3,4]. In the letter studies it has been speculated that such states may govern the dynamics during transition.

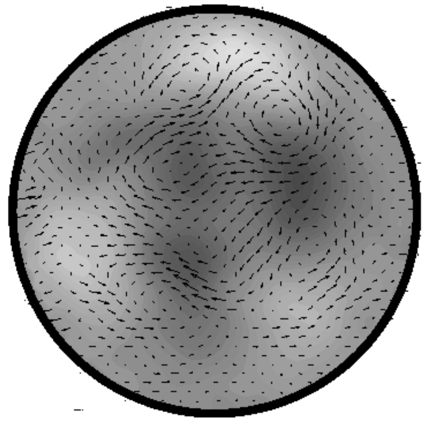

Fig. 6.1: Velocity field observed at Re=1800. Regions faster than the laminar flow are shown in light and slower ones in dark colours.

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Extensive Chaos in Fluid Convection

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Using numerical simulations we explore fundamental aspects of spatiotemporal chaos in fluid convection. We are interested in quantifying how the dimension of the dynamics varies as important system parameters are changed. We compute the spectrum of Lyapunov exponents and Lyapunov vectors to calculate the fractal dimension of the chaotic dynamics for two high-dimensional systems. We first study a phenomenological model proposed by Lorenz in 1996 now called the Lorenz-96 model [2]. By using a simple model we take advantage of the relatively low computational cost to perform very long-time simulations, over many different initial conditions, and for a wide range of system parameters. We next explore these questions for Rayleigh-Bénard convection using large-scale parallel numerical simulations for the precise conditions of experiment.

The defining feature of chaos is the sensitive dependence on initial conditions and the exponential separation of nearby trajectories in phase space [1]. We quantify this using the spectrum of Lyapunov exponents. The sum of the first N exponents describes the growth of an N-dimensional ball of initial conditions in phase space. The precise number of exponents required for the sum to vanish corresponds to the fractal dimension and is given by the well known Kaplan-Yorke formula. We compute the spectrum of Lyapunov exponents and the fractal dimension using the standard procedure described in detail in Ref. [6].

The Lorenz-96 model is a phenomenological model originally created to explore the dynamics of the atmosphere [2]. It is a one-dimensional periodic lattice of oscillators whose equations of motion contain several essential components that are important in fluid convection: a quadratic nonlinearity; dissipation; and external forcing. We have explored the dynamics over a large range of forcing and system size. In particular, we are interested in the variations of the fractal dimension for small changes in system size to gain physical insights into the fundamental composition of the underlying spatiotemporal chaos. By fixing the forcing at a small value and letting the system size increase we find that the dynamics are composed of windows of periodicity, intermittency, and of chaos. The windows of chaos are extensive, on average, and exhibit relatively large deviations on the order of 10%. The size of these windows of chaos is on the order of 4 lattice spacings whereas the natural chaotic length scale based upon the magnitude of the fractal dimension is closer to 3 lattice spacings. For an intermediate value of the forcing, we find extensive chaos for all systems that contain more than 3 oscillators and yield what we call spatiotemporal chaos. We find a systematic deviation in the dimension from extensivity that is on the order of 5% which tends to zero as the size increases.

The wavelength of these variations suggests that a single degree of freedom in the system is approximately twice the natural chaotic length scale. Finally, we explore a large range of forcing and find that the dimension follows a universal trend irrespective of system size that is captured by a power-law.

Rayleigh-Bénard convection is the buoyancy driven flow that occurs when a shallow fluid layer is heated uniformly from below [1]. We numerically solve the Boussinesq equations and corresponding tangent-space equations in cylindrical geometries with no-slip boundary conditions on all material surfaces (c.f. [4, 5]). We choose system parameters that yields spiral defect chaos [3] for large domains. We compute the Lyapunov diagnostics over a wide range of system parameters including system size [5], external driving, and fluid properties. We find extensive chaos for systems where the radius to depth ratio is approximately larger than 10. For smaller systems there is a deviation due to finite size effects where the lateral boundaries strongly influence the dynamics. A close inspection of the dynamics of the leading order Lyapunov vector reveals a transition of the convective patterns from boundary to bulk dominated dynamics as the system size is increased. We connect the dynamics of the Lyapunov exponents and the leading order Lyapunov vector with important spatial features of the chaotic flow field and find that very localized dynamics appear to be contributing significantly.
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Multi-particle statistics in turbulence measured from particle tracking experiments

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Fluid turbulence leads to a dramatic enhancement of transport and mixing and therefore is of great importance in a wide variety of natural and industrial processes from cloud physics to chemical reactors. These effects arise directly from the violent accelerations experienced by fluid particles as they are buffeted by enormous pressure gradients generated in incompressible turbulent flows. Despite the fundamental importance of these issues, only recently with the advance in detector technology (silicon strip, CMOS) it has become possible to measure the 3D particle trajectories in highly turbulent flows with high spatial and temporal resolution. Here we describe the use of a 3D direct imaging particle tracking technique that measures simultaneously the position, velocities and accelerations of many particles advected by the flow with very high temporal and spatial resolution. We report measurements of the statistical properties of turbulence both in space and in time when measured along the trajectory of particles. Properties reported will include particle acceleration, Eulerian and Lagrangian velocity structure functions, two particle dispersion, multi particle dynamics, and coarse-grained velocity gradients from Lagrangian particle tracking measurements. The results are compared with predictions from Richardson (1925), Heisenberg (1948), and Batchelor (1956).

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