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Turbulent Mixing and Beyond Workshop
Mixing in Rapidly Changing Environments – Probing Matter at the Extremes

04-09 August, 2014

The Abdus Salam International Centre for Theoretical Physics
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Turbulent Mixing and Beyond Workshop

Mixing in Rapidly Changing Environments -

Probing Matter at the Extremes

PROCEEDINGS

ABSTRACTS

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Abstracts of the Proceedings of the Turbulent Mixing and Beyond Workshop
'Mixing in Rapidly Changing Environments – Probing Matter at the Extremes', 04-09 August, 2014,
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Edited by
Snezhana I. Abarzhi, Sergei I. Anisimov, Hiroshi Azechi, Serge Gauthier, Evgeny E. Meshkov,
Joseph J. Niemela, Bruce A. Remington, and Katepalli R. Sreenivasan

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Preface

Mixing in Rapidly Changing Environments - Probing Matter at the Extremes' is the Workshop within the Program 'Turbulent Mixing and Beyond.'

The Workshop is about hydrodynamic instabilities and interfacial mixing, active and passive scalar and turbulent mixing, the evolution of phase boundaries and convection in fluids, plasmas and materials, as well as their applications in fusion, astrophysics, reactive flows, material science and aerodynamics---from atomistic to astronomical scales.

The program, 'Turbulent Mixing and Beyond,' was founded in 2007 with the support of international scientific community and of the US National Science Foundation, the US Air Force Office of the Scientific Research and its European Office for Research and Development in the UK, the US Office of Naval Research Global in the UK, the Commissariat l'Energie Atomique in France, the International Centre for Theoretical Physics in Italy (ICTP)---which is affiliated with UNESCO in Paris and IAEA in Vienna---the US Department of Energy and the National Laboratories of the Department of Energy, the Ministry of Science and Education and the Joint Institute for High Temperatures of the Academy of Sciences of Russia, the Institute for Laser Engineering in Japan, the University of Chicago, New York University and Carnegie Mellon University, the Institute of Physics and the Royal Society Publishing in the UK.

The goals of the program are to increase the visibility of non-equilibrium turbulent processes, promote rigorous development of new ideas in tackling its fundamental aspects, assist in the application of novel approaches in a broad range of phenomena where these processes occur, and have a potential impact on technology. In 2007, 2009 and 2011 the TMB Conferences were hosted by ICTP. In 2013 the theme was continued as the invited Mini-Conference, 'Mixing in Fusion Plasmas,' at the 55th Annual Meeting of American Physical Society's Division of Plasma Physics.

Rayleigh-Taylor (RT) instabilities and interfacial mixing form an important scientific theme of the program because of their ubiquitous presence and the challenges they pose: At the macroscopic scales, their properties depart from those of Kolmogorov turbulence; and at atomistic and meso-scales, their non-equilibrium features differ from standard equilibrium statistical physics. Their theoretical description has to account for the multi-scale, nonlinear, non-local and statistically unsteady character. And their numerical modeling effectively pushes the boundaries of computations and demands significant improvements of numerical methods in order to capture shocks, track interfaces, and accurately account for the dissipation processes. On the experimental front, the RT problems are a challenge to study in well-controlled laboratory environment because of their sensitivity to details. Furthermore, because of their statistical unsteadiness, systematic interpretation of experimental data is not straightforward. Despite these challenges, tremendous success has been achieved recently in large-scale numerical simulations, in laboratory experiments (especially those in high power laser systems), in technology development and in theoretical analysis.

The Book of Abstracts includes 121 contributions that are accepted at the Workshop (invited lectures, regular talks, and posters). They are sorted alphabetically within each theme. They have been reviewed by 15 members of the international Scientific Advisory Committee.

The Organizing Committee hopes that the workshop will serve to advance knowledge of the fundamental aspects of non-equilibrium turbulent processes, hydrodynamic instabilities and interfacial mixing.

S. I. Abarzhi, S.I. Anisimov, H. Azechi, S. Gauthier, E.E. Meshkov, J. J. Niemela, B.A. Remington, K. R. Sreenivasan

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Turbulence and mixing

invariant, scaling, spectral properties, scalar transports, convection

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About some possibilities of PDV method application in hydrodynamic instabilities research.

Baranov, V.K. (1); Georgievskaya, A.B. (1); Golubinskii, A.G. (1); Irinichev, D.A. (1); Meshkov, E.E. (2); Stepushkin, S.N. (1); Syundyukov, A.Y. (1); Khatunkin, V.Y. (1)
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The PDV (Particle Doppler Velocity) method possesses unique possibility to record continuous change of velocity not only for one flying object, but also for some objects (and including micro objects) which are moving simultaneously with different velocities. It opens new possibilities to research a development of hydrodynamic instabilities on accelerated surface of the condensed medium. In experiments with PDV method application a development of particles cloud which are formed in the time of appearance of a shock wave on the free unperturbed surface of a condensed medium was investigated. The condensed medium water and rosin were used. Shock waves were created by various methods:

- by laser impulse;
- electric explosion of a thin wire;
- The impactor accelerated by pressure of detonation products of acetylene and oxygen mix.

In particular, in these experiments acceleration and the subsequent sharp deceleration of a particles cloud front was observed. Also development of dispersed water clouds was observed at an exit of front of a turbulent mixing zone on free surface of the water layer accelerated by products of acetylene and oxygen mix detonation.

Exploring the effects of a rigid body on the evolution of the Rayleigh Taylor instability

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This talk discusses the effects of a rigid solid boundary impeding the evolution of the Rayleigh-Taylor (RT) instability. The classical RT instability of two homogeneous layers has been well studied through theory, experiment and numerical simulation. Yet this relatively simple sounding problem of a layer of fluid sitting on top of another less dense layer under the presence of a downward acceleration still proves to be a fascinating phenomenon to study and understand. Previous experimental studies e.g. those of Linden, Dalziel and Davies-Wykes, amongst others, used a solid rigid barrier to separate the two layers which when removed revealed the RT unstable interface. But what happens if the barrier is only partially removed? Initially the interface grows classically, however, this is soon replaced by two circulation cells, one either side of the

barrier. The circulation forces fluid from both layers onto interface at z=0, resulting in a RT mixing zone superimposed onto the circulation cells. The RT mixing zone grows as it swept across the open gap at speed U. Near to the end of the barrier the height of the mixing zone, h grows quadratically in time as x over U all squared in a manner similar to that found by Andrews and collaborators for RT mixing in water channels. Here, however, the flow is modified by the end wall. Near to the end wall the two circulation cells are deflected vertically, stretching the mixing zone vertically along the end wall rapidly. This talk will present results from low Atwood number experiments which explore the effect of different sized obstructions and the impact of the end wall. In addition, we present a simple model for the overall evolution of the mixing.

Numerical study of effect of initial perturbation spectrum on the development of gravitational turbulent mixing

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The development of gravitation turbulent mixing caused by variation in the initial spectrum of perturbations on a light/heavy material interface is studied numerically. Simulations were carried out using 2D and 3D codes. Earlier, the authors studied the development of turbulent mixing at random initial perturbations. The TMZ (turbulent mixing zone) width dependences on time in the late (self-similar) stage are close to each other in all 2D simulation, both with harmonic and random initial perturbation. The time dependences of TMZ widths in the late (self-similar) stage are close to each other in all 3D simulation, both with harmonic and random initial perturbations. The spectral distribution of velocities and scales in 3D simulations in the high-frequency range is close to the Kolmogorov distribution corresponding to the 3D simulation of turbulence. The paper also discusses the effect of local initial perturbations (which amplitudes are higher than the initial background perturbation amplitudes) on the TMZ evolution. The issue of how the choice of computational grid affects the problem solution is studied.

Sheared stably stratified turbulence and large-scale waves in a lid driven cavity

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We investigated experimentally stably stratified turbulent flows in a lid driven cavity with a nonzero vertical mean temperature gradient in order to identify the parameters governing the mean and turbulent flows and to understand their effects on the momentum and heat transfer. The experiments

have been carried out in a lid-driven turbulent cavity flow generated by a moving wall in rectangular cavity filled with air. The heated top wall and the cooled bottom wall of the cavity impose a temperature gradient in the flow which causes temperature stratification of the air inside the cavity. The turbulent velocity field in the cavity has been measured using a digital Particle Image Velocimetry (PIV) system, and the temperature field has been measured with a temperature probe equipped with twelve E-thermocouples. We found that the mean velocity patterns (e.g., the form and the sizes of the large-scale circulations and the level of small-scale turbulence inside the vortex) depend strongly on the degree of the temperature stratification. The observed velocity fluctuations are produced by the shear of the large-scale vortex. In the case of strong stable stratification, the strong turbulence region is located in the vicinity of the main large-scale circulation. We detected the large-scale nonlinear oscillations in the case of strong stable stratification which can be interpreted as nonlinear internal gravity waves. We found these waves by analyzing the non-instantaneous correlation functions of the temperature and velocity fields. The ratio of the main energy-containing frequencies of these waves in velocity and temperature fields in the nonlinear stage is about 2. The amplitude of the waves increases in the region of weak turbulence (near the bottom wall of the cavity), whereby the vertical mean temperature gradient increases. The measured intensity of the waves is of the order of the level of the temperature turbulent fluctuations.

Staircases in fluids and plasmas-structure formation from inhomogeneous mixing

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In this topical overview, we discuss the remarkable phenomena of staircase formation, where an inhomogeneous mixing process generates a profile consisting of regions of flat zones separated by sharp steps. The overall corrugation pattern resembles a staircase-hence the name. Staircases are known to form in planetary atmospheres (the Potential Vorticity (PV) Staircase), thermohaline convection, and confined plasma turbulence (the ExB staircase). Interestingly, the various mechanisms for formation proposed to date are quite different. PV staircases are thought to form by a process of self-reinforcing PV gradient sharpening, driven by PV homogenization within Kelvin Cat's Eyes produced at critical layers, where wave speed resonates with the flow speed. Thermosolutal staircase formation does not appear to involve shear flows at the fundamental level, but may be due to a kind of clustering instability produced by feedback between the coupled heat and salinity mixing processes. ExB staircases in plasma are corrugated temperature profiles supported by an array of shear flow layers situated at the steps jumps. We discuss a proposed mechanism of formation where mixing inhomogeneity results from the time delay between heat flux and gradient response. An analogy with traffic flow modeling suggests that a quasi-periodic array of heat flux jams can form, leading to the formation of staircase structure. Throughout this talk, we will endeavor to highlight similarities and difference between different staircase phenomena in different physical systems, and to highlight the open questions.

Transformation and explosive decay of flying cylindrical water shell

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Water shell is getting transformed under the influence of aerodynamic forces during its free fall. Cylindrical shell falling along its axis experiences increased pressure in the front part due to air flow and the reduced pressure at the side surface. Under the influence of pressure gradient, the shell is transformed into a disk, diameter of which increases with time. At that a deviation from the regime of free fall of the disk due to the rapid growth of the impingement air flow resistance, development of Rayleigh-Taylor instability, and destruction of the disk with formation of cloud droplets occur. This paper presents the results of an experimental study of the cylindrical water shell (45 mililiters volume, height to diameter ratio 1.23) free fall. Cross-sectional area starts to grow explosively approximately 0.7 seconds after the beginning of the fall. The falling speed in this case is approximately 7 meters per second. By that time the cross sectional area of the shell is 40 times (!) greater than its initial value. The flow was recorded by photocamera Casio Exilim EX-F1 in the mode of video shooting with a speed up to 1,200 shots per second. Experimental results with water shell allow us to understand the nature of the 2013 Chelyabinsk meteorite "explosion". The rapid increase in the transverse size of the meteorite in the final stages of its flight leads to the explosive transformation of the meteorite kinetic energy into the bow shock energy in the air and destruction of meteorite.

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Statistics, scaling laws and the local structure of scalar fields at high Reynolds numbers

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We examine the turbulent mixing of passive scalars with imposed mean gradient and varying diffusivities by means of direct numerical simulation. The Taylor based Reynolds number is varied between 88 and 529. In many applications more than one scalar is involved and the molecular diffusivity between the scalars may vary substantially leading to differential diffusion. The objective of the present work is two-fold. First, we will examine the transport mechanism within the turbulent cascade when differential diffusion is present. To this end, we derive from first principles a transport equation in correlation space that quantifies differential diffusion. This equation captures the balance between inter-scale transport, diffusive transport, scalar dissipation, as well as a transport that

originates from unequal diffusivities between the involved scalars. This equation is not closed but each term is analyzed by means of direct numerical simulation. Second, we will examine gradient trajectories of the scalar fields. The gradient trajectory can be understood as an intrinsic coordinate that is determined by the scalar field itself. Geometrical features of the scalar fields with different diffusivities are analyzed by studying the curvature field of the gradient trajectories.

Transient effects in unstable mixing layers and ablation fronts in HEDP

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We report on current investigations of transient effects in two hydro-instabilities of high energy density physics (HEDP): mixing layers and ablation fronts. Compressible and incompressible mixing layers are studied. For the latter, anelastic, low-Mach number and Boussinesq models are derived from asymptotic analysis. Large-scale simulations, using a pseudo-spectral self-adaptive Chebyshev method, have been undertaken for anelastic (for stratified unstable stack of two stable profiles) and Boussinesq (for vanishing Atwood numbers) modelings, and for the compressible Navier-Stokes equations. Stratified configurations are intrinsically unsteady: turbulence production dies as the initial density gradient vanishes. Detailed results and turbulence characteristics will be presented. Transient effects in ablation flows are studied by computing linear-perturbation responses of self-similar solutions of gas dynamics equations with nonlinear electronic or radiative heat conduction. Ablation-front distortion responses to irradiation non-uniformities are dominated, at small wavenumbers, by the mean-flow unsteadiness, inducing distortion growth approaching the mean-flow stretching rate. This unsteady effect persists at all wavelengths, amounting to a blueshift and an over-amplification of the front responses by comparison with those that would result from steady ablation-front instability modelings, and inducing finite-time response damping for any non-zero wavenumber. For surface-defect configurations, perturbation responses are sensitive to initial conditions, raising the question of perturbation transients. These different approaches bring a more realistic picture of these two HEDP hydrodynamic instabilities but it seems that we are still missing some phenomena with respect to ICF implosion stability results. Could a sharper picture be obtained from taking into account non-normal mechanisms?

Examples of extremely intermittent turbulent mixing

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Aircraft catastrophes due to equatorial icing provide examples of the extreme intermittency of turbulence in natural fluids, captured by the third hypothesis of Kolmogorov. Turbulence is defined by inertial vortex forces,

and cascades from Kolmogorov to Obukhov energy scales where the turbulence fossilizes. The intermittency factors of turbulence and turbulent mixing increase to extreme values in the ocean and atmosphere at equatorial latitudes, where horizontal Coriolis forces vanish. A famous aircraft tragedy Air France 447 was almost certainly due to equatorial icing, not pilot error as concluded in ignorance of this possibility. As shown by Baker and Gibson (1987), intermittency factors measured at the equator from ocean microstructure data imply mean to mode ratios for turbulence dissipation rates to exceed thirty thousand. Fossil turbulence and fossil turbulence waves are enhanced by beamed zombie turbulence mixing chimneys that can intermittently extend to aircraft cruising altitudes, producing a column of clear air turbulence and clear air supersaturated water vapor that cannot possibly be escaped. The tragic loss of Malaysian Airlines MH 370 has been followed by a concerted effort of airlines and governments to blame this event not on ignorance of intermittent turbulence and mixing hazards but on pilot errors and conspiracies.

Lagrangian coherent structures in turbulence

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Lagrangian Coherent Structures (LCSs) are special material surfaces that act as organizing centers for tracer patterns in unsteady flows. The recently developed variational theory of LCS enables the objective (frame-independent) detection of LCS in numerical or experimental data sets. Specifically, variational LCS theory identifies the generalized versions of classical dynamical systems structures in velocity data with general time dependence. Here I review the main results of variational LCS theory and show applications to data sets of geophysical relevance.

Turbulent mixing of a passive scalar in grid turbulence

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Fractal grids have been attracted as new-type of turbulence generators with unique characteristics. Recent study has shown that such uniqueness also appears in the near region downstream of a regular turbulence-generating grid. On the other hand, scalar mixing in such turbulences is also of great interest. In the present study, therefore, we experimentally investigate turbulent mixing in a liquid mixing-layer type flow downstream regular grid with various configurations. The mesh size is varied from 22mm to 28mm and the mesh thickness is varied from 3mm to 6mm. The typical Reynolds number based on the mesh size is set to 5000. Simultaneous measurements for two-component velocities and a concentration are carried out by particle image velocimetry (PIV) and planar laser-induced fluorescence (PLIF), respectively. The results show that turbulence intensity increases with the mesh thickness but decreases with the mesh size. With respect to

scalar mixing, the concentration mixing layer thickness increases with the mesh thickness in accordance with the turbulence intensity. On the other hand, the mixing layer thickness decreases with decreasing the mesh size, which is a different trend from the magnitude relation of the turbulence intensity. It is attributed to that the mixing layer thickness typically represents large-scale mass diffusion and the grid mesh size dominantly determines the eddy size at large scales. These facts suggest that it is better to increase both the grid thickness and grid size to enhance mass diffusion effectively.

The relay model of the bubble-front dynamics

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During the occurrence of the turbulent mixing zone on the gas-liquid interface under the Rayleigh-Taylor (RT) instability conditions the gas penetrates the liquid in the form of bubbles expanding over time. At the finite size of the front width, the number of bubbles decreases eventually to one bubble - the Taylor bubble. The bubble-front dynamics is described by quadratic time-dependence; whereas the Taylor bubble dynamics corresponds to linear time dependent. To describe transition from the RT bubble-front dynamic to that of the Taylor lone bubble a modification of the well-known model of dominant modes [1-4], whereby the bubble-front dynamics is determined by the velocity of the dominant-mode bubble evolving over time is being proposed. The point of the proposed model is to form a discrete set of dominant modes depending on the front width. The sequential ("relay") evolution of discrete dominant modes as the RT bubbles grow (with their front width staying fixed) will determine the RT bubble-front dynamics. The evolution of the bubble-front dynamics in the mixing turbulent zone on the air-water interface is illustrated by the experiments in which a container with water is accelerating (at the rate of ~1000 m/sec^2) in a 50-millimeter diameter cylindrical tube with transparent walls. The initial perturbation of the water surface is created by wooden chips with a typical size of ~1 millimeter.

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Small scale statistics in fully developed turbulence - in light of high resolution DNS

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According to the celebrated Kolmogorov's theory, the so-called K41, there exists a certain kind of universal equilibrium state in the small scale of turbulence at high Reynolds number. This idea has been confirmed to some extent by experiments and direct numerical simulations (DNS). But the equilibrium state, if it exits, may be destroyed or disturbed at least by two factors. One is the anisotropy and inhomogeneity of the flows at large scales and boundary conditions, and the other is extremely strong events/fluctuations in turbulent fields. My talk presents some discussions on these factors in the light of high resolution DNS of turbulent flows including isotropic turbulent flows, homogeneous turbulent shear flows, and turbulent channel flows.

On the mechanism of Kelvin-Helmholtz instability supression in high speed flows

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It is demonstrated that Kelvin-Helmholtz instability is suppressed in very high Mach number flows. Direct numerical simulations (DNS) and linear analysis are performed to examine the mechanism of suppression. The changing nature of pressure from a mere Lagrange multiplier in incompressible flows to a bona fide thermodynamic variable in high speed flows is shown to be the central reason for the suppression. It is shown that the wave evolution of pressure at high Mach numbers engenders a dilatational velocity field. This dilatational field ultimately suppresses the Kelvin-Helmholtz instability. Various features of the suppression mechanism will be explained in detail in the presentation. The suppression many practical consequences including the reduction of mixing at very large Mach numbers.

Instabilities of the sidewall boundary layer in a rapidly rotating split cylinder

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The structure of the sidewall boundary layer in a rapidly rotating cylinder subjected to some differential rotation has attracted much attention because of both its practical and fundamental importance. For these rapidly rotating split cylinder problems, in the absence of instabilities the interior flow is in solid-body rotation with the mean rotation rate of the two cylinder halves. For fast enough mean rotation, disturbances from instabilities can only penetrate into the interior if their frequencies are less than twice the mean rotation frequency, and then only in the form of inertial wave beams along directions determined by the frequencies. In the inviscid limit, this is governed by the inertial wave dispersion relation,but for large but finite Re and finite differential rotation, viscous and nonlinear effects come into play. Furthermore, how these inertial wave beams feed back on the boundary layer and corner instabilities is not obvious, and we try to address this.

Mixing of active scalars in variable-viscosity flows

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A remarkable property of turbulence is its ability to enhance mixing of scalar contaminants, either passive or active. The accurate prediction and/or control of these phenomena requires a thorough understanding of scalar mixing in turbulent flows and its dependence on (or, interconnection with) the dynamic field which transports it. This lecture is focused on turbulent active scalar mixing, characterized by using analytical, experimental and numerical tools. We carry out a comparison between Constant Viscosity Flows (CVF) and Variable Viscosity Flows (VVF), in shear flows. These flows are: i) a round jet of propane issuing in air (the latter is more viscous than the jet core). The viscosities ratio is up to 5. ii) a temporal mixing layer involving two streams with different viscosities. The viscosities ratio varies between 1 and 20. Viscosity variations have a non-negligible impact on mixing. VVF exhibit an acceleration of the trend towards isotropy and self-similarity. Mixing enhancement is explained by the following phenomenological scenario. Viscous host fluid blobs are enticed (via different instabilities) into the jet core. These viscous blobs represent obstacles which slow down the initial jet velocity and lead to the creation of radial velocity fluctuations behind these obstacles (wake instabilities). The rapid birth of radial velocity fluctuations accelerates the trend towards isotropy and self-similarity. Finally, transport equations for the two-point statistics are derived for both the dynamic field and the active scalar. We present closures of the third-order terms, interpreted as energy/scalar variance transferred at any scale. This kind of approach should result in a better characterization of variable viscosity flows and, on the other hand, opens new perspectives towards the development of subgrid models for Large Eddy Simulations.

Turbulent (?) mixing zone

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Development of Rayleigh-Taylor instability (RT) leads to the formation and development of what is commonly referred to turbulent mixing zone (TMZ). However, the results of experiments [1,2] point to the fact that along with the development of turbulence in the “TMZ” laminar component is present. This is expressed in the existence of permanent concentration jump of denser medium (and therefore density) on the boundary between the more dense medium and “TMZ”, and this boundary is perturbed, but not turbulent. That is the term “turbulent mixing zone” is not quite adequate and, in general, if not distorts then veils essence of the phenomenon. We can add that the development of the RT-mixing is accompanied by escalating opposite flows of matter - the penetration of less dense medium to a denser and denser in the less dense - and these flows are increasing as t squared.
To what extent this fact is combined with the turbulence?

In this connection it is interesting to note two points:

- for development of the RT mixing is necessary to the existence of a discontinuity at the boundary: more dense medium - “TMZ”;
- structure “TMZ” in the case of RT mixing at the initial stage of development is likely to be similar to the structure “TMZ” in the case of RM mixing. But over time, the differences should be manifested and grow with time, as in the case of RM mixing (unlike RT mixing) interpenetration of media will grow in proportion to ~ t.

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Vortex ring induced stratified mixing

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Understanding turbulent mixing in a density stratified environment, such as the ocean, remains an area of active research. The study of turbulence in stratified fluids is complicated by its intermittent nature, its highly vortical motion and the large range of scales in its coherent structures. In order to help reduce the problem to a more tractable form, we consider vortex rings as an idealized form of a coherent structure with a defined scale and vorticity distribution. In particular, vortex rings provide a reproducible, localized event which allow us to observe the resultant mixing once a specified enstrophy and kinetic energy distribution have been injected into the water column. We introduce vortex rings into a stably stratified two-layer fluid of varying Richardson number and observe the resultant mixing using a combination of modern imaging and measuring techniques. While previous work has looked at the effect of individual vortex rings on the stratified interface, we analyse the aggregate mixing induced over many vortex ring generations. Indeed, over successive vortex rings collisions, the mixing rate converges to a constant over a range of Richardson numbers. An analysis of this mixing will be presented along with a discussion of its implications to turbulent mixing.

Minimal flow units for passive scalars or MHD turbulence

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The interaction between velocity and magnetic fields affects the astrophysical flows. To understand the formation of strong velocity and magnetic fields a “Minimal Flow Unit” (MFU) can be used. Recent simulations considered as the MFU the Taylor-Green vortex (TG) without reaching a clear answer on the existence of a finite time singularity (FTS) for the inviscid MHD equations. The MFU consisting on two interacting Lamb dipoles (LD) could be an alternative. Viscous simulations for TG at different Reynolds number and different magnetic distributions were obtained by Lee etal 2010, observing an effect of the initial current on the vorticity evolution. Simulations at the same Reynolds number for LD and for TG with and without Coulomb force are here presented. A perfect identity between the magnetic and the vorticity components for the time evolution of TG was observed. For the LD the components of the two vectors behave similarly in the first stage, but, when the small scales in the exponential decay range form the magnetic energy spectrum at high k was greater than the vorticity spectrum. In presence of the Coulomb force the evolution is rather different. For the TG the strong early increase of the enstrophy is connected to an absence of magnetic energy growth. For the LD the enstrophy growth is greater than that for the magnetic energy. Despite the different early evolution for the two MFU, spectra with a -5/3 range are obtained wider higher is Re. The interesting feature of LD is the production of a bottleneck similar to that observed without electric forces. The Coulomb force creates the exponential range and a good Kolmogorov scaling in a short time. For TG the bottleneck was not observed and a longer time is necessary to reach a satisfactory exponential range, and Kolmogorov scaling.

Evolution of a Neutron-Initiated Micro-Big-Bang in superfluid 3He.

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A nuclear capture reaction of a single neutron by ultra-cold superfluid He-3 results in a large overheating followed by a rapid expansion and subsequent cooling of the hot sub-region, in a certain analogy with the Big Bang of the early Universe. It was shown in a Grenoble experiment that a significant part of the energy released during the nuclear reaction was not converted into heat even after several seconds. It was thought that the missing energy was stored in a tangle of quantized vortex lines. This explanation, however, contradicts the expected lifetime of a bulk vortex tangle, 10^{-5} to 10^{-4} s, which is much shorter than the observed time delay of seconds. In this Lecture I will offer a recently proposed scenario that resolves the contradiction: the vortex tangle, created by the hot spot, emits isolated vortex loops that take with them a significant part of the tangle's energy. These loops quickly reach the container walls. The dilute ensemble of vortex loops attached to the walls can survive for a long time, while the remaining bulk vortex tangle decays quickly.

Basics of Turbulent Mixing

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This talk will be a review of the work done by the speaker and his collaborators on the topic of mixing of substances by means of an underlying turbulent motion. Most attention will be given to mixing in homogeneous flows and basic configurations. Phenomena covering large ranges of the diffusivity of the mixed substances will be covered. Where possible, comparisons between experiment, theory and computations will be made; the limited amount of exact knowledge we possess will be discussed and open problems pointed out. Some discussion of mixing in more complex circumstances will be attempted.

Solving self-similar equations of k-e model in the shear turbulent mixing problem and its numerical simulation

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A system of ordinary differential equations for self-similar mode has been obtained for the known problem about shear mixing in flat mixing layer; the system solution is given in the paper. The results of numerical 2D simulation using the k-epsilon model suggest that the calculations switch to the self-similar mode. This mode is characterized by time-dependent linear growth of the turbulent mixing zone (TMZ), as well as constant in time maximum turbulent energies in the TMZ, TMZ dissipation rate functions and eddy viscosity factor. When the calculation grid is refined the simulation results tend to converge. The obtained using k-epsilon model results agree well with the analytical solution, experimental data and direct numerical 3D simulation.

An energy-enstrophy method for global stability in two-dimensional hydrodynamics

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In hydrodynamics stability theory, the standard energy method proves global or asymptotic stability by requiring the perturbation energy to decrease monotonically to zero and thus ruling out the possibility of transient growth of the perturbation. By exploiting the special role played by the enstrophy in two-dimensional fluid systems, we develop an energy-enstrophy method that lift such restriction and thus can generally establish a stronger sufficient condition for global stability. The energy-enstrophy method has potential application in a wide range of problems. We shall discuss its relevance to the absence of turbulence in the viscous Kolmogorov flow on a flat torus. Motivated by geophysical applications, we shall also applied our method to study the stability of the Kolmogorov flow on a beta-plane with a linear drag.

Cryogenic Thermal Convection - Experimental Investigation

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We present experimental results on heat transfer efficiency of cryogenic turbulent Rayleigh-Bénard convection (RBC) in a cylindrical 0.3 m cell [1]. The heat transfer efficiency described by the Nusselt number Nu = Nu(Ra;Pr) is investigated in the range of Rayleigh number $10^6 < Ra < 10^{15}$, with the Prandtl number varying from 0.7 to 15, using cryogenic helium gas with in situ tuneable properties as a working fluid. For $7.2 \times 10^6 < Ra < 10^{11}$ our data agree with suitably corrected data from similar cryogenic experiments and are consistent with $Nu \sim Ra^{(2/7)}$. Up to $Ra \sim 10^{12}$, our data could be treated as Oberbeck-Boussinesq. For Ra > 10^12, the heat transfer efficiency becomes affected by non Oberbeck-Boussinesq (NOB) effects, causing asymmetry of the top and bottom boundary layers. For $10^{12} \leq Ra \leq 10^{15}$, the Nusselt number closely follows $Nu \sim Ra^{(1/3)}$ if Nu and Ra are evaluated based on the working fluid properties at directly measured bulk temperature, T_c. In contrast, if the mean temperature is determined as an arithmetic mean of the bottom and top plate temperatures, $Nu(Ra) \sim Ra^{\gamma}$ displays spurious crossover to higher γ that might be misinterpreted as a transition to the ultimate Kraichnan regime. The second step of our analysis is to ignore the NOB effects affecting the top half of the RBC cell. We replace it by the inverted nearly OB bottom half in order to eliminate the boundary layer asymmetry, leading to the effective temperature difference, delta $T_{eff} = 2(T_b - T_c)$, where T_b denotes the bottom plate temperature, and to effective Nu_{eff} and Ra_{eff} values. The obtained effective heat transfer efficiency, showing no tendency of crossover to the ultimate regime up to 10^{15} in Ra_{eff}, is reported and discussed.

Implicit large eddy simulation of a scalar mixing layer in fractal-grid generated turbulence

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A fractal-grid generated turbulence with a passive scalar transfer is computed by an implicit large eddy simulation (ILES) for investigating a scalar mixing layer in the fractal-grid generated turbulence. In the ILES, the square-type fractal-grid with three fractal iteration is modeled by the immerse boundary method. The sub-grid scale terms in the filtered Navier-Stokes equations and the filtered passive scalar transport equation are implicitly modeled by the numerical filtering, which emulates the dissipation in sub-grid scales. The velocity statistics obtained by the ILES are compared with those obtained from the experiments using the hot-wire anemometry, which are conducted on the condition similar to the present ILES. The results show that the streamwise evolutions of mean velocity and rms values of velocity fluctuations obtained by the ILES agree well with the experimental results, and the implicit LES based on the numerical filtering is useful for predicting a fractal-grid generated turbulence. Furthermore, the passive scalar transfer in the scalar mixing

layer behind the fractal-grid is investigated. The instantaneous resolved scalar field is visualized on the x-y plane located on the center of the grid, where x is the streamwise direction and y is the direction vertical to the scalar mixing layer. It is found that the fractal-grid generated turbulence enhances the scalar transport in the y direction on this x-y plane in the downstream of the location where the velocity fluctuations generated by the biggest grid bar of the fractal-grid reach the grid centerline. The passive scalar transfer behind the fractal-grid is also discussed by using the streamwise evolution of scalar statistics.

Statistics of turbulent mixing

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This talk will investigate the statistics of turbulent mixing processes, based on calculations of 2- and 3-layer Rayleigh-Taylor mixing and shocked cylinder problems using the MILES code TURMOIL. Distributions of mixing materials, turbulence kineric energy and turbulence lengthscale will be compared to results from the AWE multiphase mix model. The calculations suggest ways in which the kinematically-distinct phases which the model treats might be identified. The shocked cylinder case generates anisotropic organized structures in the turbulence kinetic energy field, which are not directly treated by the model; however, these will not be immmediately important in driving mixing.

Direct numerical simulation and implicit large eddy simulation of Rayleigh-Taylor mixing

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In earlier work, the 3D implicit large eddy simulations (ILES) code TURMOIL has been widely used for simulation of Rayleigh-Taylor (RT) mixing, while making the assumption that the Reynolds number is high enough to have little effect on the main quantities required for engineering applications. Viscosity and diffusivity have now been included in TURMOIL so that DNS may be performed, at least at moderate Reynolds number. This has been done for two purposes (a) to quantify the effects of finite Reynolds number and Schmidt number on RT mixing and (b) to use DNS results for the highest achievable Reynolds numbers to test the validity of the ILES. TURMOIL is a compressible code and the recently implemented DNS model may be used for incompressible flows (by performing calculations at low Mach number) or for fully compressible flows with shock waves. However, DNS is limited to relatively simple situations and it is argued that ILES remains essential for more complex applications. Results will be presented for a range of recent applications including RT mixing at a plane boundary and the break-up of a thin dense fluid layer due to RT mixing.

Numerical investigation of Al_2O_3-water nanofluid turbulent convection flow through an internally ribbed pipe

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Heat transfer and pressure drop in turbulent flow of Al_2O_3-water nanofluid through an internally ribbed pipe is studied numerically. The problem of fluid flow through ribbed or grooved channels is very applicable in heat exchanger design [1-4]. Hence, researchers widely attempt to find an economic way to increase their heat transfer efficiency. An idea is to use Al_2O_3 nanoparticles in water flow to increase the heat transfer rate [5]. The effects of flow parameters, the distance between the pipe ribs, and the volume fraction of nanoparticles on the heat transfer and pressure drop in the entrance and fully-developed regions of turbulent pipe flow are investigated. In this way, the set of governing conservation equations for turbulent incompressible pipe flow in cylindrical coordinates followed by a two-layer zonal turbulence model and modified relations representing the change in nanofluid properties are discretized and solved simultaneously using a velocity-pressure coupling algorithm based on finite-volume method [6]. The obtained results illustrate that increasing the volume fraction of nanoparticles makes the thermal entrance length decrease, and consequently, the heat transfer gets increasing. It also reveals that 15 percent of increment in nanoparticles volume fraction may lead to the maximum 40 percent rise in the local Nusselt number between the ribs and about 24-percent rise in the average Nusselt number. Moreover, it can be shown that by 15 percent enhancement in nanoparticles volume fraction, the friction factor will also increase about 1.9 times in comparison with the pure-fluid turbulent flow. The results also show that increasing the pipe ribs distance by three times with a Reynolds Number of 3000 will make the average Nusselt number of nanofluid increase 1.8 times.

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Interfacial dynamics

instabilities of Rayleigh-Taylor, Kelvin-Helmholtz, Richtmyer-Meshkov, Landau-Darrieus, Saffman-Taylor, magneto-rotational and others

Stability of a hydrodynamic discontinuity

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While looking from a far field at a discontinuous front separating two incompressible ideal fluids of different densities, we identify two qualitatively different behaviors of the front (unstable and stable) depending upon whether the energy flux produced by the perturbed front is large or small compared to the flux of kinetic energy across the planar front. Landau's solution for the Landau-Darrieus instability is consistent with one of these cases, whether the gravity is present or not.

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Rayleigh-Taylor instability and accelerated interfacial mixing

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Rayleigh-Taylor instability (RTI) develops when fluids of different densities are accelerated against the density gradient; extensive interfacial mixing of the fluids ensues with time. Rayleigh-Taylor (RT) mixing controls a variety of plasma processes in high and low energy density regimes, including supernova explosion, stellar convection, and light-material interaction. RT mixing is a central concern in achieving ignition in fusion plasmas due to the seeding of RTI by the drive and target imperfections. Traditionally, it was presumed that RTI leads to uncontrolled growth of small-scale imperfections, single-scale nonlinear dynamics, and extensive mixing that is similar to canonical turbulence. The success that was achieved recently in the theory and experiments of RTI suggests a need in alternative scenarios. It appeared that the interface is necessary for RT flow to accelerate, the acceleration effects are not strong enough to freeze the turbulence even on the large scales, and the RT dynamics is multi-scale and well correlated [1-5]. This tutorial presents a physics-based consideration of RTI fundamentals, and summarizes what is certain and what is not so certain in our knowledge of RTI. The tutorial focus question - is RT accelerated interfacial mixing a disordered process indeed?

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Effect of initial conditions on late-time evolution to turbulence of Rayleigh Taylor instability under variable acceleration histories

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Rayleigh Taylor Instability (RTI) occurs at the interface between a light fluid and a heavy fluid due to gravitational impact and is observed in combustion and chemical reactor processes, pollutant dispersion, internal confinement fusion, and in Type Ia supernova formation. Traditionally, RTI has been studied under a constant acceleration; however, due to the nature of these processes, it is important to understand the evolution of RTI under variable gravitational forces. This motivates the investigation of the effects of initial conditions on self-similar evolution to turbulence of RTI under variable acceleration histories. Incompressible, three dimensional RTI is modeled using a massively parallel high resolution code, MOBILE which uses an Implicit Large Eddy Simulation (ILES) technique. In the current work, a wider a range of initial conditions are investigated to understand (a) the effect of spectral index and bandwidth on RTI for an annular initial spectra, and, (b) the effect of multiple annuli (banded spectra) with different energy content in the two bands (total energy remaining the same for all cases). Our goal is to analyze the initial condition effects on late-time evolution of turbulent RTI and to identify the similarities and differences between the Rayleigh-Taylor turbulence and the more general forms of quasi-stationary turbulence. We will discuss a large number of metrics which include low order metrics like mix widths, growth constants, molecular mixing parameter, and higher order turbulence parameters like second order moments, their dissipations, and production-dissipation ratios.

Hydrodynamics and acoustics of drops: detachment, falling and impact

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Modern experimental facility combining high speed video cameras, sensitive hydrophone different optical and contact probes were used to simultaneous registration of flows and acoustic effects during detachment, free falling and impact of drop of different liquids on liquid layers. High resolution photos, video films and sonograms illustrating dynamics and a fine structure of different flow components are presented. Processes of energy transformation are discussed taking into account mechanical and available surface potential energy and different characteristic time scales of observed phenomena. Identified mechanism of a sound emission: sounding oscillations of closed gas cavities are excited by shock impact in process of its detachment. Pressure impulse is caused by a rapid release of available potential energy surface during a break neck constriction on the bridge linking coming off the cavity with the atmosphere.

Lessons Learned from Numerical Simulations of Interfacial Instabilities over the past Decade

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Rayleigh-Taylor, Richtmyer-Meshkov and Kelvin-Helmholtz instabilities serve as efficient mixing mechanisms in a wide variety of flows, from supernovae to jet engines. In simulating these instabilities, the primary challenges are to: (1) capture all relevant physics, (2) conserve mass, momentum and energy, (3) resolve an adequate range of scales, (4) minimize numerical errors and (5) bring the results into agreement with experiments. Carefully crafted numerical simulations, like experiments, can sometimes lead to the discovery of previously unknown flow phenomena. This talk will survey some of the more interesting findings from our large-scale simulations over the past several years.

Generation of capillary waves on the surface of droplet dipping into a liquid layer

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When the free falling droplet collides with target-liquid surface, transport of droplet mass and energy takes place. The main attention of this investigation was paid to investigate first stages of shock interaction of a droplet and a liquid surface at the rest, and to visualize fine flow components. The height of free falling of a drop and drop diameter were selected from condition of wide central (cumulative) jet formation. Pure water, alcohol solutions and diluted water solutions of inks of different concentrations were used as a matter for drops and for target-liquid layers. The experimental data were obtained by means of high-resolution optical setting resolving some fast flow components of small scale (less than one hundred micrometers). As droplet dips into a liquid layer the free surfaces are annihilated, and some number of fine separated jets surrounds area of primary contact. These jets may fly out from contact area in any direction with large velocity. Some of them may fall on the colliding drop surface producing capillary waves. It was obtained that amount and frequency of capillary waves depend on energy of the interaction particularly. It is should be noted that fine jets and, respectively, a number of capillary waves were observed at the first moments of interaction already. Some periodic structures are also observed between fine jets that develop into cylindrical wreath at the later stages. Thus the flow pattern is a complex one and requires to further investigations.

Numerical simulation of pendant drop dynamics after detachment

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Precise experiments demonstrate complex behavior of a drop of fluid when it detaches from a pipette nozzle [1]. The pinch-off occurs when primarily hemispherical drop evolves into almost spherical liquid ball attached to a thin thread and this thread tears at the point of attachment. Strong shock impulse concentrated in a small area of attachment causes strong drop oscillations and determines the consequent evolution of its form. The present work is devoted to numerical simulation of these oscillations. A one-dimensional equation of motion derived from the Euler equation is used. The results of numerical simulation are compared with experimental data and then are used for correction of experimental method.

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New growth rates of non-uniformities for a spherically converging shock

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The shock wave is a most basic and important hydrodynamic phenomenon in many different branches of high-energy density physics. In converging geometries such as cylinders and spheres, a shock wave is cumulatively strengthened towards the center and exhibits asymptotically self-similar behavior [1]. Thereby it has been widely recognized that a spherically converging shock wave is always unstable [2]. Their analysis is an approximation based on the CCW (Chester-Chisnell-Whitham) theory, and are thus valid for relatively low modes. Here we present a rigorous linear theory for a spherically converging shock and resultant new growth rates of non-uniformities [3], to show that a cut-off mode number exists, over which perturbations are diminished. This result is expected to give significant revision to our understanding on the nature of a spherically converging shock wave.

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Richtmyer-Meshkov instability in plasmas - Magnetohydrodynamic evolutions and the dependence on equation of state

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Richtmyer-Meshkov instability (RMI) plays a crucial role in various plasma phenomena such as astrophysical supernova explosions and inertial fusion implosions. One of the urgent and curious questions related to the RMI is the interaction with a magnetic field. It is known that there are two important effects brought by the inclusion of an external field, which are the amplification of the ambient field and the suppression of the unstable growth. We demonstrated by direct numerical simulations (DNS) that the magnetic field can be amplified through the stretching motions driven by the RMI. The maximum field strength is more than two orders of magnitude higher than the initial size, and it appears associated with the interface as well as the bulk vorticity left by the rippled transmitted shock. The growth of RMI can be reduced significantly by a strong field as a result of the extraction of vorticity from the interface. A useful formula describing a critical condition for magnetohydrodynamic RMI has been introduced, and which is successfully confirmed by DNS. The critical field strength is found to be largely depending on the Mach number of the incident shock. We also examine the dependence of the growth velocity of the RMI on the equation of state. The linear growth velocity is determined by not only the size of the circulation generated at the interface but also the effects of the bulk vortecity left behind the rippled shock surface traveling away from the interface. It is found that the stabilization by the bulk vorticity cannot be negligible when the fluid is highly compressible, which is shown simply by the parameter study of the specific heat ratio in the perfect gas equation of state.

High energy density physics

inertial confinement and heavy-ion fusion, Z-pinches, light-mater and laser-plasma interactions, non-equilibrium heat transfer

Suppression of Rayleigh-Taylor instability and its Application to Impact Ignition

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A double ablation scheme[1] to suppress the Rayleigh-Taylor instability (RTI) has been proposed for a direct-drive inertial fusion target, in which two ablation surfaces driven by thermal radiation and electron conduction are formed separately. The growth of RTI is significantly suppressed due to the large ablation velocity and long density scale. By employing the double ablation scheme, we performed integrated experiments on impact ignition [2,3]. In the impact ignition scheme, a portion of a deuterated polystyrene (CD) shell is accelerated to about 600 km/s and is collided with precompressed CD fuel. The kinetic energy of the impactor is efficiently converted into thermal energy generating a temperature of about 1.6 keV. We achieved a two-order-of-magnitude increase in the neutron yield by optimizing the timing of the impact collision, demonstrating the high potential of impact ignition for fusion energy production.

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Effect of initial amplitude on the interfacial and bulk dynamics in the Richtmyer-Meshkov instability under conditions of high energy density

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We systematically study the effect of the initial amplitude on the inter-facial and bulk dynamics of the Richtmyer-Meshkov instability (RMI) induced by strong shocks. The shock propagates from the light to the heavy fluid. The fluid densities differ significantly, with Atwood numbers up to 0.95. The fluid interface is initially perturbed with a cosine wave perturbation. Its amplitude is varied from 0% to 100% of the initial perturbation wavelength. A broad range of the shock strengths and density ratios is considered. Smoothed particle hydrodynamics code is employed to ensure shock capturing and interface tracking [1,2]. Detailed diagnostics of the flow scalar and vector fields is performed. Whenever possible the simulation results are compared with existing theoretical analyses achieving good agreement. The focus question of our study is how the energy deposited by the shock is partitioned between the inter-facial and volumetric components. We analyze the dependence of the initial growth-rate of RMI, the velocity away from the interface, and the transmitted shock velocity as functions of the initial amplitude. Particularly, we found that for a Mach

number 5 and an Atwood number 0.8, the initial growth rate is highest and the inter-facial energy is the largest when the initial amplitude is about a quarter of the wavelength.

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A platform for high-energy-density hydrodynamic shear experiments on the NIF

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A counterflowing shear-induced mixing experiment originally fielded on the Omega Laser Facility has been scaled to and implemented on the National Ignition Facility. The shear experiment platform drives 100 km/s shocks into each side of a foam-filled shock tube bisected by an Al tracer plate. After the shocks cross in the tube center, a region of strong shear is created (~150 km/s velocity difference from one side of the plate to the other) while eliminating any net pressure gradient across the tracer. As the shear instability takes effect, the tracer layer begins to mix with the surrounding foam and expand into the tube volume. The expansion of the layer is diagnosed by x-ray radiography. Developing non-linear structures within the layer are also imaged as the instability progresses toward the transition to turbulence. The shear flow can be sustained for ~10 ns on Omega and ~30 ns at NIF, allowing the mixing to proceed and to be compared against models. Data from the Omega and NIF experiments have been interpreted in simulations using the LANL radhydro code RAGE and in the context of Reynolds-averaged-Navier-Stokes (RANS) models. The successful implementation of the counterflowing shear experiment on NIF suggests that the platform, which uses indirect drive to continually drive the hydrodynamics in the shock tube for at least 10 ns, could be adapted to a number of other hydrodynamic mixing and turbulence experiments in the HED regime.

Simulating and Diagnosing Shell RhoR Perturbations and Hot-Spot Mix in NIF Capsule Implosions

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The growth of perturbations in ICF capsules can lead to significant variation in in-flight shell areal density (RhoR), and result in mixing of dense material into the hot-spot (H-S). Experiments on the National Ignition Facility (NIF) have provided clear evidence of ablator mix, consistent with simulation predictions,[1] however

a detailed understanding of the individual sources of perturbation growth and their relative contribution to H-S mix remains a challenge. Seeds for perturbations include "isolated defects" on the capsule, the fill-tube (10-μm-diam, for filling capsule with gas), and the "tent" (~ 50-nm-thick plastic which supports the capsule). These seeds are high-mode number, making both the simulations and experimental measurements challenging. In this talk, we report on plans and progress in developing quantitative methods to infer the growth and resulting mix. As the capsule is accelerated inward, the perturbation growth results from the initial shock-transit phase and then amplification by Rayleigh-Taylor (R-T). Measurements of RhoR perturbations in capsules after reaching peak velocity are essential to our understanding. We plan to employ "self-backlighting", where emission from the H-S is enhanced prior to peak compression by adding high-Z gas to the fill, producing a bright continuum x-ray source at hu~8 keV. From images of the transmitted x-rays, above and below the K-edge of an internally doped high-Z layer (Cu), we will infer the growth of various seeds, resolving up to mode ~60. After the capsule decelerates, the resulting H-S mix can include ablator material (CH), or "payload" (DT fuel or CH for non-cryo targets). The relative contributions to mix can be determined by doping capsules with different high-Z materials and observing characteristic x-ray emission - allowing an estimate of mixed mass (spectroscopy) and identification of the sources of mix (imaging).

[1] Hammel, B.A., HEDP, 6 (2010). The work is prepared by LLNL under Contract DE-AC52-07NA27344

Rayleigh-Taylor in accelerated solids

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Rayleigh-Taylor instability (RTI) in accelerated solids has been a subject of intensive research in the last decade. This is mainly because, on one hand, RTI may be a matter of concern in many experiments on high energy density physics as it may affect its performance. On the other hand, RTI in solids has become a unique tool for the evaluation of the mechanical properties of solids under extreme conditions of pressure and at very high strain rates. The linear analysis of the instability based in the usual normal modes results to be an inappropriate approach in this case because it can only describe the asymptotic behaviour of the instability. Therefore, the essential initial transient phase in which the solid go through the transition from the elastic to the plastic regime cannot be treated. We have developed an approximate theory based on the Newton second law that allows for considering the evolution of the RTI since the initial stress free (or any given initial stress conditions) going through elastic-plastic transition. We have found a stability criterion and shown that the occurrence of such a transition is not equivalent to the condition of instability, even though if it is a necessary condition (but not sufficient) for instability. Thus, a stable region exists in which the solid is in the plastic regime. The model also provides the complete linear evolution of the instability for the different kinds of stable and unstable solutions. We have considered interfaces of elastic-plastic solids with different media, namely, ideal fluid, elastic solid, viscous fluid, and viscous fluid with a magnetic field diffused in its interior. These different cases correspond to situations of relevance to geophysics and to liner implosions driven by an intense ion beam and by a magnetic field generated by intense electrical currents.

Novel regimes of fluid flows, instabilities, and mixing in high energy density settings

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Hydrodynamic instability and mix experiments on high power, high energy lasers used in inertial confinement fusion (ICF) and high energy density (HED) science research have been under development for well over two decades. A wide range of geometries have been explored, including planar, cylindrical, and spherical, and combinations thereof. The instabilities that have been looked at include the Rayleigh-Taylor, Richtmyer-Meshkov, Kelvin-Helmholtz, Widnall, and Weibel instabilities. A wide range of regimes in HED settings have been explored, including "pure hydrodynamics" and hydrodynamics affected by radiation, magnetic fields, (solid-state) material strength, direct-drive laser imprinting, and collisionless electrostatic and electromagnetic instabilities. I will give examples of experiments exploring these different types of flows and instabilities, and the ensuing fluid interpenetration and mixing. Time permitting, I will discuss in more depth some of the newer and more novel regimes being explored, such as instability growth strongly reduced or "turned off" entirely by solid-state material strength, and collisionless plasma interpenetration strongly impeded by Weibel and other plasma instabilities.

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Progress in the understanding of instability growth in Inertial Confinement Fusion implosions on the National Ignition Facility

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Inertial Confinement Fusion (ICF) implosions are being conducted on the National Ignition Facility (NIF) at the Lawrence Livermore National Laboratory. The goal of these experiments is to compress a spherical shell of cryogenic deuterium-tritium (DT) fuel to sufficiently high densities and temperatures to produce fusion energy gains greater than unity. This compression is driven on NIF by a series of laser-driven shock waves that propagate through a spherical polystyrene (CH) ablator shell that surrounds and drives the implosion of the DT fuel layer. Critical to the success of ICF is the understanding and control of instabilities that occur at both the ablation surface and the interior ablator / DT ice interface. Both interfaces are unstable to the Richtmyer-Meshkov and Rayleigh-Taylor instabilities. The Mach number of the driving shocks and the Reynolds numbers of the unstable interfaces are quantified to assess the degree to which turbulent mixing plays a role in these implosions. In order to benchmark

our ability to simulate instability growth at multiple interfaces, driven by multiple shocks, a new series of experiments have been initiated, in which single and multi-mode initial perturbations are machined on the unstable interfaces to provide a well-characterized initial condition. High-resolution radiographic measurements are used to quantify instability growth in conditions nearly identical to those occurring in ignition implosions. Results from an initial series of experiments quantifying ablation front instability growth are presented showing good agreement with simulations for capsule radial convergence by a factor of 2-5. Two different ablative drive histories are compared, demonstrating the ability to reduce the ablation-front instability growth by a factor of approximately four. Similar measurements are currently being prepared to quantify growth at the ablator / ice interface and to extend these measurements to higher convergence ratios.

Three-dimensional simulations of National Ignition Facility implosions with mix and low-mode shape perturbations

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The National Ignition Facility (NIF) uses the world's most energetic laser to compress a spherical layer of fusion fuel over 35 times in radius. At these compressions, loss of spherical symmetry leads to failure of the implosion to heat and produce DT fusion. Recent experiments with improved laser pulse shapes, known as high foot pulses, have reduced the propensity for the NIF targets to mix due to Richtmyer-Meshkov and Rayleigh-Taylor instabilities. However, there remain asymmetries at longer wavelengths thought to be caused by aspherical radiation drive. We report here on advances to our three-dimensional (3D) radiation hydrodynamics simulation capabilities using HYDRA. Simulation advances include full Monte Carlo particle transport for nuclear burn and diagnostics processes, resolution of lower-energy DD neutrons, and updated mesh management to allow large, low-mode spherical harmonic perturbations. We have also further advanced our 3D post-processing to generate simulated diagnostics, including time-integrated neutron images, detailed neutron spectra, and time-resolved x-ray imaging with enhanced spectral resolution. The advanced simulations and the resultant simulated diagnostics reproduce many surprising aspects of the NIF experimental trends. Puzzles that may be explained include longer burn durations, large and strongly direction-dependent ion temperatures, and large neutron-weighted bulk velocities. We present in particular 3D simulations of low-mode perturbed implosions, both with and without contamination of the central hot spot by ablator mixing. The improved simulations suggest diagnostic signatures that can be examined to determine more fully the impacts of low-mode asymmetry and fine-scale mix. We also discuss future controlled NIF experiments designed to test our capabilities to accurately model 3D implosions.

Accelerated dynamics of blast wave driven Rayleigh-Taylor instabilities in high energy density plasmas

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We report the systematic analysis of experimental data describing the late time evolution of the high Mach number and high Reynolds number Rayleigh-Taylor instability which is driven by a blast wave. The parameter regime is relevant to high energy density plasmas and astrophysics. The experiments have been conducted at the Omega laser facility [1]. By processing the experimental x-ray images, we quantified the delicate features of RT dynamics, including the measurements of the curvature of the transmitted shock and the interface envelopes, the positions of RT bubbles and spikes, and the quantification of statistics of RT mixing. The measurements were performed at four time steps and for three different initial perturbations of the target (single mode and two two-mode). We found that within the noise level the curvatures of the shock and interface envelope evolve steadily and are an imprint of laser imperfections. At late times, the bubble merge does not occur, and the flow keeps significant degree of order [1,2]. Yet, the blast-wave-driven RT spikes do accelerate with the power-law exponent smaller than that in case of sustained acceleration. We compared the experimental results with the momentum model of RT mixing and stochastic model achieving good agreement.

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Non-equilibrium processes

unsteady, multiphase and shock-driven turbulent flows, anisotropic non-local dynamics, connection of continuous description at macro-scales to kinetic processes at meso and micro scales

The Rayleigh-Taylor instability of the Newtonian and non-Newtonian fluids

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The present work is devoted to the Rayleigh-Taylor instability (RTI) of visco-plastic, dilatant and pseudoplastic fluids. The main aim of the work was to carry out numerical simulation of mixing of two media with different rheology and getting the relationship between development of the instability and the characteristic properties of non-Newtonian fluids. The theoretical study is given for mass transport and momentum in the non-equilibrium turbulent processes with regard to their anisotropic statistically unsteady, inhomogeneous and multiscale nature to find patterns in the spectra of turbulent motions generated by RTI, a quantitative description of large-scale invariance. We performed Direct Numerical Simulation (DNS) of turbulent flows arising from the development of RTI. During the numerical experiments of the Rayleigh-Taylor instability with the multimode perturbation of the contact boundary it was found that the stirring of dilatant fluid is similar to the mixing regime of the Newtonian fluid. Thus, the corresponding coefficients of turbulent mixing have similar values. Increase in the width of mixing bands for visco-plastic and pseudoplastic liquids are significantly different from that for the Newtonian fluid. It can be seen that the dependence of $h(Agt^2)$ is not linear and has a quadratic form. In addition, it is shown that the development of the hydrodynamic instabilities leads to a vortex cascade that corresponds to the development stage of the vortices in the energy and the inertial range during the transition to the turbulent flow stage. The results obtained show that the emerging flows and the study parameters for inviscid and viscous cases are identical.

Turbulence in the presence of thermal non-equilibrium

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We consider statistical features of turbulent flows in the presence of thermal non-equilibrium (TNE). This situation is typically encountered in flows with shock waves but can also be recreated in laboratories where lasers can be used to excite specific internal modes of various molecular systems. Although the asymptotic behavior of many steady laminar flows in TNE is well know, the effect of turbulent fluctuations has been virtually unexplored in a systematic way. Our objective here is to determine statistical features of internal energy modes, in particular vibration, when the advecting flow is turbulent. We show that turbulent fluctuations create statistically steady states that, unlike

laminar flows, do not approach thermal equilibrium at long times. This has implications on the distribution of energy in different modes, namely, turbulent kinetic energy, and vibrational and translational internal molecular modes.

Using geometric representations to find periodic orbits in the Lorenz system

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The world is filled with chaotic and complex systems, whether it is the traffic patterns of city's, weather patterns, information flow in the internet, or turbulence in fusion reactors. These complex systems are not often amenable to simple analytic solutions. The many degrees of freedom and sheer size of these systems makes statistical mechanics an alluring choice to try and understand them. Yet traditional equilibrium Boltzmann Gibbs theory is inadequate for the job, thus requiring a non-equilibrium extension. We present one such novel extension for understanding the complex dynamics of these systems using the Observable Representation, which has been successfully applied to complex systems in detailed balance. The theory was recently extended to non-detailed balance systems i.e those with non-zero currents of probability by constructing a new transition matrix which accounts for this flow of probability. Using this new matrix it was shown that chaotic properties of the logistic map can be controlled. In this talk we utilize the Observable Representation to control chaos in the famous Lorenz System, which has widely been used as a dynamical model for weather. Specifically, we show how to change chaotic orbits to periodic orbits in the Lorenz system. The novelty of this method is that one can construct the representation from experimental data without any knowledge of the equations of motion. This method demonstrates that a suitable choice of the metric between states can reveal the key chaotic properties of the underlying system, which can then used to be implement a control strategy.

Multiphase equations of state for metals under intense pulsed influences

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Models of thermodynamic properties and phase transformations of materials are critical for numerical simulations of processes under intense pulsed influences such as, for example, ultrashort laser irradiation or shock waves. Reliability of simulated results is determined mainly by adequacy of thermodynamic description of the matter behavior. In the present talk, multiphase equations of state for metals are considered. A model of thermodynamic potential Helmholtz free energy is presented with taking into account polymorphic phase transformations, melting and evaporation effects. Equation-of-state calculations have been carried out for beryllium, aluminum, titanium, niobium, tungsten and some other metals over a broad region of the phase diagram. Obtained results are compared with available data from experiments at high energy densities.

Two-phase expansion of tin droplet heated by a short laser pulse: cavitation, foaming and formation of shell in stretched metastable liquid

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EUV (Extreme Ultraviolet) lithography uses an EUV light of the extremely short wavelength of 13.5 nanometers. It allows exposures of line circuit patterns with a half-pitch below 20 nanometers that cannot be exposed by the conventional optical lithography [1]. Putting it into practical use requires a variety of element technologies, including the light source. Double laser pulse scheme is introduced for a high efficiency EUV source [2], in which a short pre-pulse heats a liquid tin droplet with a size of the order of 20 micrometers in diameter. Expansion dynamics of a laser-heated tin droplet has been investigated with the use of both radiation hydrodynamic code (R-Hydro) and combined Monte Carlo - molecular dynamic code (MC-MD). It is shown that expansion of droplet is directed by compression and tensile waves generated by ultrafast energy deposition of laser pulse within a thin surface layer of a droplet. Important features of its expansion dynamics simulated by MC-MD are nucleation of bubbles and cavitation in stretched metastable liquid. Cavitation in the inner part of droplet is followed by formation of foam-like material surrounded by a liquid shell, which is similar to what was observed in exploding wires [3]. Results of MC-MD and R-Hydro simulations are compared. We discuss influence of the EOS on R-Hydro simulation of a tin droplet, in particular a role of the very small sound speed in the two-phase liquid-vapor expansion flow. Nonuniform laser irradiation leading to non-symmetrical expansion is also studied.

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Plasmas

fusion plasmas, coupled plasmas, anomalous resistance, ionosphere

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Turbulence spreading in magnetized plasmas

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Turbulence in magnetically confined fusion plasmas can spread from the region where instabilities grow to the linearly stable zone [1]. This turbulence spreading can significantly modify the transport scaling based on the local flux-gradient relation, and affect the performance of future fusion devices. This presentation will review our previous nonlinear fluid theoretical model for turbulence spreading [1,2] and gyrokinetic and gyrofluid simulation results [3-6] which exhibit turbulence spreading. Finally, implications of turbulence spreading on transport barrier dynamics are discussed.

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Controlled Study of VLF and HF Wave Interactions with Space Plasma at Arecibo Observatory

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We report our whistler wave injection experiments, which have been conducted at Arecibo Observatory in the past 25 years, starting with the joint US-USSR Active Space Plasma Program experiment on December 24, 1989. A series of controlled whistler wave experiments with Arecibo HF heater were subsequently carried out during 1990 - 1998. In these ionospheric HF heating experiments, 28.5 kHz whistler waves were launched from the nearby Naval transmitter (code-named NAU) located at Aguadilla, Puerto Rico. HF heater waves were used to create ionospheric ducts (in the form of parallel-plate waveguides) to facilitate the entering of NAU whistler waves from the neutral atmosphere into the ionosphere. Conjugate whistler wave propagation experiments were conducted between Arecibo, Puerto Rico and Trelew, Argentina in 1997. In the next 15 years or so (1999 - ongoing), we conducted whistler wave experiments in the absence of an HF heater. Naturally-occurring large-scale ionospheric

irregularities (due to spread F or TIDs) were relied on to guide NAU launched 40.75 kHz whistler waves to propagate from the ionosphere further into the radiation belts. We plan to use the newly built Arecibo HF heater and NAU VLF transmitter together with Arecibo UHF and microwave radars for further study of whistler wave interactions with space plasma.

Acoustic gravity waves generated in HF heated ionospheric plasmas

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We report controlled study of the coupling between plasma and neutral turbulence in HF ionospheric plasma heating experiments, carried out at Gakona, Alaska. It is expected that temperature gradients of neutral particles in the heated ionospheric region can be created. We observed that naturally-occurring anomalous heat sources can potentially generate acoustic gravity waves (AGW). Based on these observations we have conducted a series of experiments at Gakona since 2008, using the high power HF heater at HAARP, to simulate AGW excitation by anomalous heat source. A UHF radar (MUIR), an Ionosonde, and GPS satellites were used to diagnose the concerned coupling between neutral-plasma turbulence. The data from satellite passes and ground-based radio diagnostic instruments have provided good indications that HF wave-induced AGW/TIDs radiated away from the heated ionospheric plasma volume. In summary, based on the TEC scan measurements, we can estimate the propagation speed of AGW to be a few tens of m/s. We notice that AGW originated from the edge of the heated region, as expected. Skymap measurements showed the radially propagating disturbances, in the direction opposite of the bulk plasma drift. The line-of-sight (LOS) Doppler measurements by UHF radar pointing outside of the heated plasma volume revealed periodic Doppler shifts with periodicity, which matches the RF modulation cycle.

Temporal and spatial evolution of ion acoustic turbulence during ionospheric HF heating

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We have been conducting ionospheric HF heating experiments at Gakona, Alaska, aimed at controlled study of plasma turbulence for better understanding of Earth and space environment. While high-power HF waves can produce large-scale as well as short-scale ionospheric turbulence, we report our theoretical and experimental study of short-scale plasma density perturbations associated with ion acoustic waves. Backscatter radar detected ion acoustic waves, known as ion lines, showed temporal and spatial variations. To identify HF wave-induced ion acoustic waves, we monitored the background ionospheric plasma conditions, using HAARP MUIR radar, magnetometers, riometers, digisonde etc. We reported observations of spatial distribution of Langmuir waves due to down-going propagation [1]. These experiments corroborate our theoretical prediction that PDI excited Langmuir waves propagating to lower altitudes to reach optimum conditions for Langmuir wave cascading [2]. Our recent data analysis of ion lines, using energy flow analysis technique, further verifies the theory of [2]. In this paper we show that the coupling of PDI-excited Langmuir waves via ponderomotive force can be the source to generate forced ion acoustic waves. This process is similar to the beat wave generation with difference frequency of two electromagnetic waves [3]. Some prominent features of HF-enhanced ion lines, e.g., asymmetric spectra, can be reasonably explained.

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Generation of ionospheric plasma waveguides/ducts above Arecibo, Puerto Rico using HF and microwave transmitters

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In our earlier study we show that microwaves, if intense enough, can excite filament-type waveguides/ducts in ionospheric plasmas [1]. If the Arecibo 2.38 GHz radar is used as the transmitter, kilometer-scale waveguides in the form of filaments can be generated in the microwave-heated ionospheric region above Puerto Rico. By contrast, parallel-plate waveguides can be created by HF heater waves as we have demonstrated in Arecibo experiments [2] and Gakona/Alaska experiments [3]. These HF wave-induced waveguides facilitate the coupling of NAU-launched 40.75 kHz whistler waves into the ionosphere, as seen in our conjugate whistler wave propagation experiments conducted between Arecibo, Puerto Rico and Trelew, Argentina [4]. A series of controlled whistler wave injection experiments have been conducted subsequently at Arecibo, to investigate whistler wave-plasma interactions in the ionosphere and whistler wave-charged particle interactions in the inner radiation belts [5]. In this paper we report research on coordinated operation of Arecibo HF heater and

microwave radar. These experiments are aimed at investigating: (1) effects of microwave-induced plasma density irregularities on HF heater waves and 40.75 kHz whistler waves, and (2) comparison of ducted whistler waves propagation and interactions with ionospheric plasmas under different configurations of artificial waveguides (viz., filament- or parallel plate-shaped ionospheric ducts).

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Self-organization by maximizing entropy on a foliated phase space

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We formulate a macroscopic hierarchy as a Casimir leaf of degenerate Poisson manifold, and study the grand-canonical ensemble on the foliated phase space. The invariant measure on the leaves is mapped to an inhomogeneous metric over the reference-frame phase space, by which the thermal equilibrium may have a structure. The theory is put to the test by constructing a self-consistent vortical solution that simulates a self-organized magnetrospheric plasma. Whereas a canonical Hamiltonian mechanics has a natural symplectic structure determined by a regular (full rank) Poisson operator (field tensor), a general noncanonical Hamiltonian system is endowed with a Poisson operator that may have a nontrivial kernel; the corresponding degenerate Poisson manifold may be split into some local symplectic leaves (Lie-Darboux theorem). A Casimir element guides us to delineate the leaves of the Poisson manifold; the gradient of a Casimir element belongs to the kernel of the Poisson operator, i.e., a Casimir element is a constant of motion. Here we proffer a physical interpretation: a Casimir element is an adiabatic invariant that is separated from a coarse-grained microscopic angle variable - a Casimir leaf is a macroscopic hierarchy. On reflection, a Casimir invariant may be unfrozen by recovering a corresponding angle variable. Such an increase in the number of degrees of freedom is formulated as a singular perturbation. In this talk, we examine this framework by analyzing the kinetic model of a plasma.

Astrophysics

supernovae, interstellar medium, star formation, stellar interiors, early Universe, cosmic-microwave background, accretion disks

Linking 1D Stellar Evolution to 3D Hydrodynamic Simulations

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Stellar evolution models of massive stars are important for many areas of astrophysics, for example nucleosynthesis yields, supernova progenitor models and understanding physics under extreme conditions. Depending on which stage of its evolution a massive star is in, it may have many different convective boundaries, separating fluids of different chemical composition on either side. Within these boundaries nuclear fusion will occur either in the core or in 'shells'. The study of these boundaries and their properties are important for determining the remaining evolution of a star. In this talk I will present initial results of a study on convective boundary mixing (CBM) in massive stars. General properties of convective boundaries are investigated. The 'stiffness' of a convective boundary can be quantified using the Bulk Richardson number, this is the ratio of the potential energy for restoration of the boundary to the kinetic energy of turbulent eddies. A 'stiff' boundary will suppress CBM, whereas in the opposite case a 'soft' boundary will be more susceptible to CBM. Typical values of Bulk Richardson numbers for 'stiff' and 'soft' boundaries are 10,000 and 10, respectively. One of the key results obtained so far is that lower convective boundaries (closer to the center) of nuclear burning shells are 'stiffer' than the corresponding upper boundaries, implying limited CBM at lower shell boundaries. This is in agreement with 3D hydrodynamic simulations (e.g. Meakin and Arnett 2007). This result also has implications for nuclear burning flame front propagation in Super-Asymptotic Giant Branch (S-AGB) stars and also the onset of novae.

Neutrino radiation transport in core-collapse supernovae

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Core-collapse supernovae (CCSNe) are the explosive deaths of massive stars. On a timescale of seconds, its iron core collapses to nuclear densities and launches an outward-propagating shock, which eventually disrupts the star in a supernova-enriching the Universe with heavy elements, and leaving behind a neutron star or a black hole. We are developing modeling capabilities to study CCSNe using leadership-class supercomputers [1]. This requires accurate solution of the coupled system of equations for self-gravity, hydrodynamics, and neutrino radiation transport. About 99 percent of the gravitational energy released during iron core collapse is radiated away in the form of neutrinos, and energy transfer from neutrinos to the stellar fluid is the major driver of the explosionâ€”aided by convection and shock instabilities. This paradigm is supported with recent CCSN simulations based on multigroup, flux-limited diffusion neutrino transport [2]. However, in a CCSN, neutrino heating occurs under non-equilibrium conditions (neutrinos are semi-transparent to the stellar fluid), and a description based on the relativistic Boltzmann transport equation [3] is warranted. In this work describe our efforts to develop more realistic models of CCSNe. We focus on the neutrino transport problem, and highlight the challenges, which include dimensionality, strong gravitational fields and relativistic fluid velocities. We discuss our recent work on developing robust, high-order discontinuous Galerkin methods for solving the Boltzmann equation. Our first goal is to evaluate some transport approximations that permeate modern, multi-dimensional CCSN models.

[1] C. Cardall et al., ApJS, 210, 17 (2014); [2] S. Bruenn et al., ApJ, 767, L6 (2013); [3] C. Cardall, E. Endeve, and A. Mezzacappa, Phys. Rev. D, 88, 023011. Research partially supported by the Office of Advanced Scientific Computing Research, US Department of Energy.

Turbulence in the solar wind, spectra from Voyager 2 data

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A description of the spectrum of the solar wind has not been fully established, in particular in the outermost part of the helioshpere where, beyond the termination shock, the solar wind interacts with the interstellar medium. This work shows the solar wind spectra deduced from the data recorded by the Voyager 2 mission, which allows us to resolve the velocity and particle density fluctuations between 10^{-5} and $4x10^{-3}$ Hz, i.e. in the MHD inertial range of solar wind. We used two data sets: 1979 data, acquired when Voyager was at about 5 astronomical units from the sun, and 2007-2013 data when it crossed the termination shock and entered the heliosheat. These data are incomplete time series, more lacunous as the craft moves away from the sun (45 percent missing data in 1979, 97 percent in 2012). We have estimated the spectra by extracting almost complete subsets and filling small gaps, up to three consecutive missing data, with polynomial interpolation. Then, a global DFT for irregularly spaced data is also used. The 1979 data show a nice power law fit. The exponents, -1.63, -1.57 and -1,52 for the radial, equatorial and polar velocity components respectively, show the presence of anisotropy, but are suggestive of a Kolmogorov-like inertial range. Preceded by a small bump in the equatorial and polar components only, there is a gradual steepening of the spectrum above $3x10^{-4}$ Hz, which resembles the behaviour of plasma turbulence at the transition between MHD and kinetic ranges. The 2007-2013 data, too sparse, have been preprocessed by a low rank matrix completion reconstruction technique. These preliminary results have been analyzed by introducing the sequence of gaps observed in the Voyager data to velocity datasets extracted from direct numerical simulations of incompressible Navier-Stokes turbulence as well as synthetic turbulence and by comparing the relevant spectra.

Evolution and observational signatures of primordial magnetic fields

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Observations show that galaxies have magnetic fields with a component that is coherent over a large fraction of the galaxy with field strengths of order microGauss. These fields are supposed to be the result of amplification of an initial weak seed magnetic field of unknown nature. A recent study, based on the correlation of Faraday rotation measures and MgII absorption lines (which trace halos of galaxies) indicates that coherent microGauss-strength magnetic fields were already in place in normal galaxies (like the Milky Way) when the Universe was less than half its present age. This places strong constraints both on the strength of the initial magnetic seed field and the timescale required for amplification. Understanding the origin and evolution of these fields is one of the challenging questions of modern astrophysics. In this talk I will address the primordial magnetogenesis scenario, and discuss how does a seed field evolve during the evolution of the universe, including during phase transitions and the formation of cosmic structure. I will address observational signatures of primordial magnetic fields, such as the effects on cosmic microwave background radiation, Sunaev-Zeldovich effect, the first object formation, halos abundance, big-bang nucleosythesis, etc.

Numerical investigation of relatvistic shock-vortex interaction

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Interaction of a plane relativistic shock wave with single vortex is investigated numerically on the basis of relativistic hydrodynamics equations in two-dimensional formulation. The attention is focused to the vorticity production during the interaction and the influence of the Lorentz factor. Related problem of shock-vortex interactions in a submerged non-stationary relativistic jet is considered. It is shown that the instability development of a high-energy supersonic relativistic jet with an appropriate choice of the problem parameters is accompanied by the interaction of the vortex system generated by the Kelvin-Helmholtz instability with the shock wave in which the jet's matter decelerates. A high resolution numerical scheme is used to provide resolution of vortices subjected to Lorentz contraction in presence of strong relativistic shock waves.

A linear theory of the relativistic Richtmyer-Meshkov instability

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The Richtmyer-Meshkov instability is of crucial important in astrophysical phenomena and laboratory experiments. The RMI occurs when an incident shock hits a corrugated interface separating two fluids. The interface corrugation induces a ripple of shock surfaces of the transmitted and reflected shocks. An important type of astrophysical shock is the relativistic shock, in which the shock velocity is a non-negligible fraction of the speed of light. These shocks are unique to astrophysical environments, and are theoretically expected in gamma ray bursts, active galactic nucleus jets and in some types of supernova explosions. An important feature of the relativistic shocks is that the transverse velocity across the shock fronts is not preserved under Lorentz transformations, which is different from non-relativistic shock case. Since the RMI is essentially driven by the velocity shear left by the rippled shocks at the interface and in the fluid, the growth of the RMI in the relativistic flows is not the same as that in the classical ones. Here we discuss about the linear growth rates of the relativistic RMI following an analytical formulation driven by Wouchuk and Nishihara [1]. Namely we solve linear wave equations in the area between the transmitted and reflected shocks with proper boundary conditions for the rippled shock fronts and the rippled interface for the relativistic flows.

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Turbulent mixing in plasma astrophysics. Weakly compressible turbulence in local interstellar medium

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Turbulent mixing is one of the most important phenomena, both in astrophysical and in laboratory plasmas. Compressible MHD turbulence in the local interstellar medium is studied using the Large Eddy Simulations (LES) method for turbulence modeling. Notwithstanding the fact that supersonic flows with high values of large-scale Mach numbers are characterized in the interstellar medium, nevertheless, there are subsonic fluctuations of weakly compressible components of the local interstellar medium. These weakly compressible subsonic fluctuations are responsible for the emergence of a Kolmogorov-type density spectrum in interstellar turbulence which is observed from experimental data. In this work, it is shown that density fluctuations are passive scalars in a velocity field in weakly compressible MHD turbulence and demonstrate Kolmogorov-like spectra in the inertial range of the energy cascade and are coincident with those for kinetic energy. The spectral indices of density fluctuations and kinetic energy are shown to be almost coincident and close to a

k^{-3} spectrum in dissipative range. The decrease of energy-containing large eddies and inertial range with time and the increase of dissipative scale are also represented. It is shown that the turbulent sonic Mach number decreases significantly from a supersonic turbulent regime, where the medium is strongly compressible, to a subsonic value of the Mach number, describing weakly compressible flow. This conclusion about the reduction of the role of compressibility in turbulent fluctuations is confirmed by examination of time evolution of the velocity divergence which decreases and tends to zero. In the interstellar medium, the transition of MHD turbulent flow from a strongly compressible to a weakly compressible state do not only transforms the characteristic supersonic motion into subsonic motion but also reduces plasma magnetization.

The role of the magnetic field in the evolution of the stellar rotation of young low mass stars

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The current picture of the evolution of the stellar rotation of young low mass stars reveals the main role of the stellar magnetic field. Dipole magnetic field strength is thought to arise from dynamo action, an interplay of rotation and turbulence within convectively unstable regions. Is therefore expected some dependence of magnetic strength on stellar rotation. Unfortunately dynamo theory itself is not yet able to provide the desired relation and we must turn to use rotational indicators as vsini measurements or photometric periods with age. We developed a dynamical model for the angular momentum evolution. Computations were done between the birth-line in 0.03 up to to 4900 Myr. The model incorporates four mechanisms for angular momentum transport between the star and the interstellar medium: 1) disk-locking and stellar winds powered by accretion during early stages, 2) stellar magnetized wind and internal angular momentum transfer during the main sequence. The model also includes changes in the star mass and radius, an exponentially decreasing accretion rate and the effect of the opening of the stellar magnetic field lines, as expected to arise from the star-disk interaction during the T Tauri stage. We used a simple linear dynamo prescription for the rotational dependence of the stellar field. Even if such as prescription lack of validity for fully convective stars, the bulk of the rotational predictions are in agreement with observational data coming from extensive photometric monitoring as reported in the literature.

Magneto-hydrodynamics

magnetic fusion and magnetically confined plasmas, magneto-convection, magneto-rotational instability, dynamo

Energetics, mixing and acceleration in spontaneously reconnecting environments

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Magnetic reconnection is a process which results in the so-called solar flares, X-ray bursts of up to $6x10^{33}$ erg from above the solar surface. It also governs coronal mass ejections that release a cloud of energetic particles, sometimes reaching the Earth and causing magnetospheric storms. The dayside and nightside reconnection in the Earth magnetosphere allows fast particles to penetrate closer to Earth and often affect satellites. One of the key values in this process is the reconnection rate, measured in units of Alfven speed. While laminar reconnection scenarios predict the reconnection rate to go to zero with the dissipation coefficients, such as magnetic diffusivity, it was found that it actually goes to a constant, 0.015, due to the development of spontaneous turbulent reconnection. This implies that there are inherent large-scale dissipation, mixing and resistance in nearly-ideal systems with thin current sheets. It also happened that such spontaneous reconnection events result in the acceleration of particles, which explains the release of hot particles in magnetically-dominated environments, such as solar corona.

Nonhelical inverse transfer of a decaying turbulent magnetic field

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In the presence of magnetic helicity, inverse energy transfer from small to large scales is well known in magnetohydrodynamic (MHD) turbulence and has important applications in astrophysics, cosmology, and fusion plasmas. Using high resolution direct numerical simulations, we report a similar inverse transfer even in nonhelical MHD turbulence. We compute for the first time spectral energy transfer rates to show that the inverse transfer is about half as strong as with helicity, but in both cases the magnetic gain at large scales results from velocity at similar scales interacting with smaller-scale magnetic fields. We argue that in both cases, the inverse transfer is a consequence of the universal k^4 and k^2 subinertial range spectra for magnetic and kinetic energies, respectively. The shallower k^2 spectrum forces the magnetic field to attain larger-scale coherence. The inertial range shows a clear k^{-2} spectrum and is the first example of fully isotropic magnetically dominated MHD turbulence exhibiting weak turbulence scaling.

Self-organization and transport processes (e.g. momentum) in high energy plasmas

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The idea that self-organization processes are present in well-confined plasmas and that the consideration of them together with that of the basic collective modes which can produce the observed transport of important parameters such as the plasma thermal energy and, more recently, the angular momentum, was proposed originally [1] in 1980. Since then, the "principle of profile consistency" has been verified frequently and extended and the near constancy of the "loop voltage" in ohmically heated axisymmetric plasmas has been observed repeatedly with machines of different size and characteristics. The latest developments of transport analyses that take these factors into account are presented referring in particular to the experimentally discovered spontaneous rotation phenomenon and to the properties of meaningful fusion burning plasmas to be produced by future experiments.

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Explosive mixing in Magnetized Plasmas

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The explosive release of energy from magnetically confined plasmas produces some of the most dramatic and destructive natural phenomena. In such events a slowly evolving plasma suddenly erupts releasing a significant fraction of its stored magnetic, gravitational or pressure energy in a few tens of dynamical times (which is typically the Alfven time or the free fall time). The stored energy is converted into some combination of heat, energetic particles, fast plasma flows and/or radiation. Tokamak disruptions, solar flares, coronal mass ejections, magneto-spheric sub-storms and edge localized modes in tokamaks all exhibit this type of explosive behavior. The eruption of multiple flux tubes in a magnetized plasma atmosphere is proposed as a mechanism for explosive release of energy in plasmas. Stable isolated flux tubes are shown to be metastable in a model line tied magnetized atmosphere. The energy released by destabilizing such field lines can be a significant fraction of the gravitational energy stored in the system. This energy can be released in a fast dynamical time.

Energy and cross-helicity measurements of two magnetic flux ropes embedded in a argon magnetoplasma

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Flux Ropes are magnetic structures of helical field lines, accompanied by spiraling currents. They are naturally occurring and are commonly observed in solar, space, or laboratory plasmas. These ropes are time-dependent, turbulent, and three-dimensional in nature. In this laboratory experiment, two flux ropes (length L=10 m, current I=150 amps) were created in the Large Plasma Device (LAPD) at UCLA (Bo=330 G, Te=4eV, Ar). These highly kink unstable ropes violently oscillate, interact, and reconnect. Both the magnetic field and the ion flow were measured in this experiment using a 3-axis magnetic field probe and a Mach probe, respectively. Due to the large scale of flux ropes in the solar and magnetopause environment, magnetohydrodynamic (MHD) is often an apt description of their formation and interaction. In such an approximation, both the energy and cross-helicity are invariant. While the total energy shows small oscillation at the kink frequency, the cross-helicity, the correlation between the flow and the magnetic field, is invariant but non-vanishing. This is an indication of strongly non-linearly interacting Alfven waves. The turbulence that occurs in this circumstance is called "imbalanced." If turbulence is a driver of the system, then the time-averaged cross-helicity of fluctuations in the data (for a given frequency range) will yield localized patches (eddies) of positive and negative cross-helicity. Such localized sign flipping is prevalent inside the flux ropes when their temperature greatly exceeds that of the background magnetoplasma.

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Theoretical study of anisotropic MHD turbulence with low magnetic Reynolds number

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Anisotropic turbulent flows are ubiquitous in engineering, geophysical and astrophysical sciences. Flows of electroconducting fluids under the action of external magnetic field present an example of strongly anisotropic turbulence. Such flows are not only important for different engineering applications, but also provide an interesting framework for studies of quasi-two-dimensional turbulence with strongly modified transport properties in easily controllable laboratory experiments. We present theoretical results that advance our understanding of magnetohydrodynamic (MHD) flows with low magnetic Reynolds number by treating this phenomenon within the quasi-normal scale elimination (QNSE) theory. Previous applications of the theory to turbulent flows with stable stratification and solid body rotation have demonstrated that QNSE is

a powerful tool for studies of anisotropic turbulent flows. We derive expressions for scale-dependent eddy viscosities and eddy diffusivities in the directions parallel and normal to the external magnetic field and investigate progressive anisotropization of turbulent transport of momentum, kinetic energy and passive scalar. The theory yields analytical expressions for anisotropic one-dimensional spectra of MHD turbulence and passive scalar. In particular, the theory sheds light upon the modification of the Kolmogorov minus five-thirds spectrum by anisotropic Ohmic (Joule) dissipation.

Azimuthal and helical magnetorotational instabilities to non-axisymmetric perturbations

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Short-wavelength stability analysis is made of axisymmetric rotating flows of a conducting fluid subjected to external axial and azimuthal magnetic field. The instability is referred to as the helical magnetorotational instability (HMRI), among which the instability caused only by the azimuthal magnetic field is referred to as the azimuthal magnetorotational instability (AMRI), Non-axisymmetric perturbations, when coupled to azimuthal magnetic field, makes unstable rotating flows of a wider variety of angular-velocity profiles. We determine the range of unstable angular-velocity distribution and the overall maximum growth rate for the HMRI and AMRI. Then a global stability analysis is made for limited cases. We highlight the viewpoint of the Hamiltonian spectra by calculating energy of waves.

Self-generated magnetic fields in Rayleigh-Taylor unstable laser produced plasmas

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Laser-solid interactions have long been known to produce self-generated magnetic fields. These fields are caused by thermoelectric currents, which are developed in hot nonuniform plasma (the Biermann battery effect). Self-generated magnetic fields in Rayleigh-Taylor (RT) unstable plasma have been investigated in experiments at the Omega Laser Facility. Thin plastic foils were irradiated with a ~2-ns laser pulses at an intensity of a ~1014 W/cm^2. Target modulations were seeded by laser nonuniformities and amplified during target acceleration. Megagauss-level magnetic fields were measured by employing radiography with a ~10- to 50-MeV protons. The experimental data show the evolution of magnetic fields following the nonlinear RT growth in the targets. Two-dimensional magnetohydrodynamic simulations show good agreement with the experiments. These simulations predict a moderate effect of self-generated magnetic fields on the RT growth through altering heat transfer between the critical and ablation surfaces of the targets.

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Nonlinear dynamics of non-uniform current-vortex sheets in magnetohydrodynamic flows

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A theoretical model is proposed to describe nonlinear dynamics of interfaces in MHD flows based on an idea of non-uniform current-vortex sheet. Nonlinear evolution of the interface is found to be determined by the Alfven and Atwood numbers. The model is tested by MHD Richtmyer-Meshkov instability with sinusoidal vortex sheet strength. Numerical solutions reproduce properly the results of MHD simulations, such as stability conditions, exponential growth of magnetic field, and its saturation. We expect that our model can be applicable to the interface motions in a wide variety of MHD flows, such as MHD Kelvin-Helmholtz instability or MHD Rayleigh-Taylor instability.

Geophysics and Earth Science

physical oceanography, turbulent convection under stratification and rotation, planetary interiors, mantle-lithosphere tectonics

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Differential fluid mechanics - coupled analytical, numerical and laboratory modeling of environmental processes

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Examples of a regular fine structure of flows of various scales: from light-years away in the interstellar space, to thousands of kilometers and meters in the atmosphere and hydrosphere of the Earth observed by modern terrestrial and space-based optical instruments are presented. Under laboratory conditions, a fine structure of flow patterns with scales ranging from centimeters to microns is visualized. Evolution patterns of a dye or a fine suspension in propagating and standing waves as well as markers transport in compound vortices are demonstrated. The mathematical modeling of dynamics and flow structure is based on the fundamental set of governing equations. Equation set describing momentum, substances and energy transport in fluids and a closing state equation are selected. The symmetries of the set, unlike many model systems correspond to the basic principles of physics. The rank of the set, the order of its linearized version and degree of characteristic algebraic equation are defined by compatibility condition. A complete classification of large and coupled fine components of periodic flows is given for fluids of low viscosity. Condition of observability of physical quantities is discussed. Periodic and lee internal waves accompanied by fine components generated by compact 2D and 3D sources performing linear and torsion oscillations were calculated by asymptotic methods and compared with data of schlieren visualization of wavy flow patterns. Pre-calculations are in good agreement with experiment. Flow pattern of diffusion induced flows in stationary stratified medium on oblique strip and wedge was done on Lomonosov MSU supercomputer. Extrapolation of modeling results on environmental conditions is discussed.

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Disrupting bacteria accumulation by chemotaxis in heterogeneous flow structures and incomplete mixing conditions

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Subsurface bacteria influence the environmental dynamics by controlling the complex bio-geo-chemical reactions driving many important processes (such as geothermal, EOR, or bioremediation). The large-scale consequences result from the microscale interactions occurring within the subsurface heterogeneous host medium. At these microscopic scales, the subsurface environment is very heterogeneous, and both chemicals and microbes experience incomplete mixing conditions due to a huge heterogeneity of chemical and physical gradients. Using microscopy and microfluidics we assess the relationship between the heterogeneous flow and mixing within a simplified analogous porous medium and the characteristic microorganism resident time within the host medium. When injecting a front of water we observe bacteria accumulation in well defined, flow controlled structures, which impact the resident time of microorganisms in the host medium. When repeating the experiment injecting a chemoattractant, the observed microorganisms accumulation in flow-driven structures result to be disrupted by their chemotactic behavior.

Solute blob evolution in a Darcy scale heterogeneous porous medium: Topological controls of mixing

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We study the mixing behavior of a dissolved substance that evolves from a solute blob in a heterogeneous porous medium. The study scale is mesoscopic so that flow is governed by Darcy's law. Flow heterogeneity is induced by spatially variable hydraulic conductivity. The fundamental mechanism governing the evolution and mixing dynamics of a solute blob are the competition of stretching and compression of a material element as well as local shear on one hand, and diffusion on the other. We formulate the transport problem in a Lagrangian framework and transform the equation of motion of the solute particles that form the blob into the coordinate system attached to the material element on which it originates. In this frame the particle dynamics are explicitly related to the Lagrangian deformation of the material element, and thus to the topology of the flow field. The blob evolution is fully characterized by the time series of Lagrangian stretching and shear rates in the coordinate system of the material element. Their stochastic dynamics are analyzed in terms of the fluctuations of the strain angles and the orientation of the material strip. We derive stochastic evolution equations for these quantities, and link their evolution to the topology of the flow field. Mixing is measured in terms of the evolution of the probability density function of concentration, the mixing volume as quantified by the dilution index, and the destruction of concentration contrast as

quantified by the scalar dissipation rate. We derive a predictive framework for the evolution of these observables, and evaluate the mixing efficiency for different flow topologies.

Geostrophic turbulence in rotating Rayleigh-Benard convection

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Rotation influences thermal convection in a multitude of ways: from changing the mechanism of pattern formation near onset for weak rotation to enhancing heat transport through Ekman pumping in turbulent thermal boundary layers. Recently there has been significant interest in the geostrophic range of rotating convection where, except in the cores of spatially localized vorticies and near solid boundaries, Coriolis forces balance pressure gradients. This geostrophic range occurs when rotation is dominant over thermal buoyancy, i.e., when the Rossby number is small. I will describe recent experimental work on rotating convection in cryogenic helium and in water. In helium gas we explore the heat transport dependence on Rayleigh and Ekman numbers in a new range of those parameters compared with previous work. In water we have made local measurements of vertical heat transport and characterized the relative contribution of convective Taylor columns to overall global heat transport. Through comparison of these experimental results with numerical simulations and theory of rotating convection by others, a reasonable description of the geostrophic thermal convection regime is emerging.

Mixing-induced dissolution in unstable reactive flow

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The evolution of porosity in carbonate reservoirs during CO_2 injection, and the wormhole formation in karst aquifers can be attributed to fast equilibrium reactions, which are characterized by large Damkohler numbers. Under these conditions the reaction rate is mixing-controlled, and can be quantified in terms of the mixing rate of the conservative components of the chemical system.

Here, we study the calcite dissolution during the convective-driven mixing of CO_2 in a carbonate aquifer. We derive an analytical expresion for the speciation contribution to the reaction rate which is valid under a wide range of reservoir conditions (pH less than 8.3). This allows us to analyze systematically the impact of conservative mixing mechanisms on the dynamics of the complex reactive flow system. We explore the evolution of the porosity and the permeability by means of numerical simulations of a CO_2 stationary layer dissolving into brine using an analogue-fluid system with a non-monotonic density-concentration curve. Our findings show how the developed porosity patterns depend on the fingering instabilities caused by the convective-driven dissolution of the CO_2, the movement of the receding CO_2-brine interface, and the properties of the chemical system.

Pore-scale origin of anomalous transport in 3D porous media

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We study the origin of non-Fickian particle transport in 3D porous media by simulating fluid flow in the intricate pore space of real rock. We simulate Stokes flow at the same resolution as the 3D micro-CT image of the rock sample, and simulate particle transport along the streamlines of the velocity field. We find that transport at the pore scale is markedly anomalous: longitudinal spreading is superdiffusive, while transverse spreading is subdiffusive. We demonstrate that this anomalous behavior originates from the intermittent structure of the velocity field at the pore scale, which in turn emanates from the interplay between velocity heterogeneity and velocity correlation. Finally, we propose a continuous time random walk model that honors this intermittent structure at the pore scale and captures the anomalous 3D transport behavior at the macroscale.

Stretching, coalescence and mixing in porous media

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We present a theoretical framework for modeling mixing in disordered porous media based on elementary deformation and aggregation processes. The scalar mixture is represented as an ensemble of stretched lamellae evolving by diffusion and coalescence [1]. Detailed numerical simulations in Darcy scale heterogeneous permeability fields are used to analyze the lamella deformation process, which controls the local concentration gradients and thus the evolution of the concentration mixture through stretching enhanced diffusion. The corresponding Lagrangian deformation process is shown to be well modeled by a Langevin equation with multiplicative noise, which can be coupled with diffusion to predict the temporal evolution of the concentration probability density function (PDF). At late times, lamella interaction is enforced by confinement of the line within the dispersion area. This process is shown to be well represented by a random aggregation model, which quantifies the frequency of lamella coalescence and allows predicting the temporal evolution of the concentration PDF in this regime. The proposed theoretical framework provides an accurate prediction of the concentration PDFs at all investigated times, heterogeneity levels and Peclet numbers.
In particular, it relates the temporal behavior of mixing, as quantified by concentration moments, scalar dissipation rate or spatial increments of concentration, to the degree of structural heterogeneity.

[1] Le Borgne et al. Phys. Rev. Lett. 2013

Diffusion-driven flows on a wedge-shaped obstacle

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Inhomogeneity of fluids density in the environment and technological devices is given by temperature or dissolved substances concentration distributions. It causes existence of a number of specific flows such as internal waves and a medium fine structure [1]. The fundamental equations set for inhomogeneous multi-component fluids mechanics is used to describe the phenomena. It includes continuity, momentum balance, temperature, substance concentration and closing state equations. The fundamental set is solved numerically in the full nonlinear formulation using finite volume method realized in original solvers of the open source package, OpenFOAM, on cluster systems. As a demonstration of the approach the problem on evolution of diffusion-driven flow on topography is solved. As an impermeable obstacle placed into a continuously stratified medium a wedge-shaped body with curved lateral boundaries is considered. Due to breaking of naturally existing background diffusion flux of stratifying agent by impermeable surface of the wedge a complex multi-level vortex system of compensatory fluid motions is formed around the obstacle [2]. Parametric analysis of the problem including horizontal scale and opening angle of the wedge, as well as value and sign of curvature radius of its lateral edges is of a great particular scientific and practical interest as to investigation of influence of the mentioned parameters on the stratified flow structure and dynamics. Edge effects play a crucial role in generation of extended high-gradient horizontal interfaces which are formed as a result of slope jet flows separation from the sharp edges of the obstacle. Formation of an intensive zone of pressure depression in front of the leading vertex of the wedge is responsible for generation of propulsive mechanism resulting in a self-motion of the obstacle along its neutral buoyancy horizon in a stably stratified environment.

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Turbulent transport at a simplified clear air/cloud interface

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We consider a simplified physics of the could interface where condensation and evaporation are neglected and momentum, thermal energy and water vapor transport is represented in terms of the Boussinesq model coupled to a passive scalar transport equation for the vapor phase. The interface is modeled as a layer separating two isotropic turbulent regions with different kinetic energy and vapor concentration. In particular, we focus on the small scale part of the inertial range as well as on the dissipative range of scales which are important to the micro-physics of warm clouds (Reynolds number Re_lambda= 250). We have numerically investigated stably stratified interfaces by varying the local stratification at the cloud interface. The physical parameters are set to values met at an altitude of about 1000 meters (Prandtl number Pr=0.74, Schmidt number Sc=0.64) while the Froude number at the interface ranges from 0.8 to 8. The kinetic energy ratio is equal to 7. The initial evolution resembles the mixing in a non-stratified flow. However, as the buoyancy term becomes of the same order of the inertial one, the phenomenology of the system changes. We observe a spatial redistribution of the kinetic energy and a concomitant onset of a well of kinetic energy in the low energy side of the mixing layer. In this situation, the mixing contains two interfacial regions with opposite kinetic energy gradient, which in turn produces two intermittent layers in the velocity field. This generates a change in the structure of the fluxes, dissipation rate, temperature and water vapor with respect of the non stratified mixing: the communication between the two turbulent region is weak, and the growth of the mixing layer stops. These results are discussed and compared with laboratory and numerical results with and without stratification.

Angular momentum “unmixing” and anisotropic turbulence - laboratory experiments

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As vertical mixing of density changes available potential energy, mixing of potential vorticity (PV) changes the angular momentum. In the former case, mixing results from the interplay between internal gravity waves and anisotropic turbulence with direct energy cascade, in the latter case the mixing results from the interplay between Rossby waves and turbulence with inverse cascade. The analogy between the “elasticity” of internal gravity waves and Rossby waves is explored to develop a novel method for estimating characteristics of large-scale turbulence. The method employs PV monotonizing with latitude. The rms of the displacements from the monotonic profile yields a length scale, Lm, analogous to the Thorpe's scale, Lt. The Thorpe scale is proportional to the Ozmidov scale, Lo. In small-scale forced quasi-two-dimensional turbulence with a beta-effect and inverse energy cascade, the analogue of Lo is a scale Lb which marks the threshold of spectral anisotropy. It is proportional to a scale at which the turbulent eddy turnover time is equal to a Rossby wave period. Laboratory experiments in a rotating tank with electrolytic solution as a working body, Lorentz force-generated small-scale forcing and a beta-effect due to the parabolic shape of the free surface demonstrate that Lm is approximately equal to Lb. This proportionality, established for the first time, is further substantiated in studies of lateral diffusion using the finite scale Lyapunov exponent (FSLE) method based upon the reconstruction of Lagrangian trajectories. After initial separation, the diffusion attains the Richardson and then the Taylor regime. The scale of the transition between the regimes is close to Lb which is a trademark of the regime of near-zonostrophic turbulence. The closeness between Lm and Lb enables one to estimate the rate of the inverse cascade, the coefficient of the meridional diffusivity and, generally, diagnose important characteristics of planetary macroturbulence.

Rayleigh-Taylor Instabilities and mon-equilibrium plasma dynamics in rapidly changing ionospheric environments

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Turbulent hydrodynamic mixing induced by the Rayleigh-Taylor (RT) instabilities occurs in settings as varied as exploding stars (supernovae), inertial confinement fusion (ICF), and macroscopic flows in fluid dynamics such as ionospheric plasmas. I review physics-based predictive modeling and novel multi-nesting computational techniques developed to characterize dynamics of strongly inhomogeneous non-Kolmogorov ionospheric media in rapidly changing environments. Rapid distortion theory and nested numerical simulations of ionospheric plasma density structures associated with nonlinear evolution of the Rayleigh-Taylor (RT) instabilities in Equatorial Spread F (ESF) are presented. For the limited area and nested simulations, the lateral boundary conditions are treated via implicit relaxation applied in buffer zones where the density of charged particles for each nest is relaxed to that obtained from the parent domain. The equation for the electric potential is solved at each time step with a multi-grid method. The high resolution in targeted regions offered by the nested model is able to resolve scintillation producing ionospheric irregularities associated with secondary RT instabilities characterized by sharp gradients of the refractive index at the edges of mixed regions. We examine the organizing mixing patterns for plasma flows due to polarized gravity wave excitations in the neutral field, using Lagrangian coherent structures (LCS). Our studies focus on the charge-neutral interactions and the statistics associated with stochastic Lagrangian motion.

Coriolis-induced redistribution of turbulent kinetic energy and atmospheric scintillations

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The Reynolds Averaged Navier-Stokes (RANS) equation, albeit exact, is unclosed and requires an additional equation that links the local Reynolds stress with the local mean velocity field. This strategy has been employed for more than a century to study the low-order statistical properties of turbulent mixing of mean momentum [1][2]. A recently developed algebraic closure model for the Reynolds stress has been formulated [3] as a non-negative mapping of the NR-stress into itself. Consequently, the closure is a priori realizable for all turbulent flows. Most significantly, the theory predicts that the coupling between the Coriolis acceleration and the fluctuating velocity in spanwise fully-developed rotating channel flows causes the primary and the secondary normal Reynolds momentum flux differences to flip signs in the outer flow region on the high pressure side of the symmetry plane. It is noteworthy that this redistribution of energy by the Coriolis acceleration occurs in a region where the intrinsic mean vorticity is zero. The workshop presentation will also illustrate that a Coriolis-induced anisotropy in the index-of-refraction of the atmosphere may provide a practical means to determine the relative latitude and the relative longitude between two points on an orthodrome. Thus, atmospheric scintillation phenomenon caused by a Coriolis-induced redistribution of turbulent kinetic energy may be an essential component in the mechanics of bird orientation and navigation.

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Flow fine structure around an impermeable obstacle in a continuously stratified environment

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The environmental systems are mostly non-homogeneous in space and variable in time due to non-uniform distributions of dissolved or suspended matters, gas bubbles, temperature, medium compressibility and the influence of external forces. A stably stratified fluid, which is formed due to the combined influence of a medium non-homogeneity and the Earth's gravitation, is known to be a thermodynamically non-equilibrium system. This gives rise to formation of fluid motions even in the absence of purely mechanical reasons. Among such phenomena are convective flows driven by spatial variations in fluid density or the so-called diffusion-induced flows on topography [1]. The study of such flows has received much attention in laboratory studies and numerical and analytical modeling because there are abundant instances of the phenomena in environmental systems. The numerical study of diffusion-induced flows on an impermeable obstacle reveals a system of jet-like flows formed along its sloping boundaries and a complicated structure of circulation cells attached to the surface of the obstacle [2]. The most intensive structures are clearly registered experimentally by Schlieren techniques in form of horizontally extended high gradient interfaces attached to extreme points of an obstacle (plate's sharp edges, cylinder's poles, wedge's vertices, etc.). With increase of typical velocities these structures do not disappear but are transformed into a complicated system of thin interfaces separating different kinds of disturbances, e.g. internal waves and a vortex sheet [3]. The structural elements of extremely slow flows of non-homogeneous fluids form a flow fine structure in rapidly changing environments. The calculated flow patterns are compared with the results on exact solution of the analogous linearized problem and the Schlieren images of stratified flows around both motionless and moving obstacles.

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Wall-Bounded Flows

structure and fundamentals, non-canonical turbulent boundary layers, including unsteady and transitional flows, supersonic and hypersonic flows, shock-boundary layer interactions

Non-equilibrium accelerating turbulence in round tubes: inhibition of Reynolds stress

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Direct numerical simulations of temporally accelerated turbulent pipe flow reveal modification of the coherent structures due to acceleration. Two types of simulations are performed: a) fully developed turbulent flow subjected to constant mean acceleration, and b) evolution of a single hairpin eddy subjected to the same acceleration. The initial eddies are extracted by conditional averaged flow fields associated with second-quadrant Reynolds shear stress events from DNS data of the fully developed turbulent pipe flow at the initial Reynolds number. In the case of fully turbulent initial flow, the temporal acceleration increases the Reynolds number from ReD=5,300 to 26,500, and the response of the turbulence is found to be delayed relative to the response of the mean flow, as also reported by previous studies. The delay causes the ratio of velocity induced by the hairpin to the mean velocity to decrease below the threshold value needed for nonlinear formation of new hairpin vortices from the initial hairpin. The autogeneration of new hairpin vortices is suppressed, resulting in reduction of turbulent transport and, consequently, reduction of skin friction. The occurrence of auto-generation blocking in other wall flows exhibiting drag reduction suggests that it may be a useful concept for explaining and devising drag reduction strategies.

Numerical and experimental study of the free flow speed increase in a set of guiding surfaces

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Wind or flowing water kinetic energy can be harnessed and used in many types of renewable energy facilities. The efficiency of such facilities strongly depends on the kinetic energy flux in the flow. The goal of our study is to explore a possibility of a kinetic energy flux increase in hydrodynamic flows employing the cumulative phenomenon in the guiding surfaces system . Optimization of the kinetic energy flux is based on theoretical evaluations and predictions, 3D numerical simulations and laboratory experiments. We use commercial CFD solver STAR-CCM + for 2D and 3D numerical simulations of the flow. The mathematical model, numerical procedures, and the computer codes are verified using experimental results. Numerical results show good agreement with theoretical evaluations. A laboratory tank made in the shape of a vertical rectangular channel is developed for the experimental study. It provides a uniform laminar flow of water at of 15 sm/s rate and up to 10 seconds long. The flow is created once the water starts to flow out through a drain hole in the bottom of the tank. Numerical simulations have shown the possibility of 3-4 times velocity increase in a single set of guiding surfaces (one "cascade") with the kinetic energy flux increase up to 20-25 times. We plan to continue our research further along experimentally and theoretically testing several cascades joint action results. By placing one cascade inside the other we create a flow multistage accelerator. Thus, we apply cumulative phenomenon for the kinetic energy flux increase of a free flow.

Reduced modeling for exact coherent structures in parallel shear flows

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In plane Couette flow, the lower branch Nagata solution has been shown to follow simple streamwise dynamics at large Reynolds numbers. A decomposition of this solution into Fourier modes in this direction yields modes whose amplitudes scale with inverse powers of the Reynolds number, with exponents that increase with increasing mode number [1]. In this work, we use this scaling to derive a reduced model for exact coherent structures in general parallel shear flows. The reduced model describes the dynamics of the streamwise-averaged flow and of the fundamental fluctuations and is regularized by retaining higher order viscous terms for the fluctuations. Numerical methods are designed to find good approximates of nontrivial solutions which are then converged using a preconditioned Newton method. This procedure captures both lower branch and upper branch solutions and demonstrates that these branches are connected via a saddle-node bifurcation, thereby extending related results by Hall & Sherwin [2] and Blackburn et al. [3] for plane Couette flow beyond the lower branch.

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Active flow control by local periodic forcing on surface of a tested model

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A lot of active flow control techniques have been developed for purposes of drag reduction and lift amplification based on prevention of flow separation and transition to turbulence, as well as energy spectra redistribution. The present work is focused at numerical investigation of flow structure and dynamics affected by application of a number of flow control methods including deformable surfaces, blowing/suction, DBD plasma generation and local surface heating. Among the existing methods of laminar-turbulent transition delay an important role is given to flow control techniques based on generation of perturbations similar to that of boundary layer developing along the surface of a tested model. One of such methods consists in application of either passive visco-elastic or actively oscillating deformable surfaces which have proven effective in controlling downstream intensity of boundary-layer eigen perturbations [1]. The numerical results demonstrate possibility of maintenance of these perturbations by varying phase speed, wave length and amplitudes of surface oscillations that prevents early laminar-turbulent transition. As an effective low-energy consumption flow control method for an air flow DBD actuators are often used, which combine effects of air blowing

and local surface heating due to high local values of temperature and direct mechanical impact on the surrounding air through intense ionic wind [2]. To study the pure mechanical impact of DBD actuators on air flow numerical tests were conducted to investigate effects of local periodic blowing from a slot on the surface of a tested model, which is realized numerically by introduction of local periodic oscillations into the velocity field. As a geometric configuration for the model a circular cylinder is considered that offers an excellent opportunity to test flow control methods since it exhibits a plenty of fluid dynamic phenomenon, while being immune to geometrical variation such as airfoil shape.

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Combustion

dynamics of flames and fires, deflagration-to-detonation transition, blast waves and explosions, flows with chemical reactions, flows in jet engines

Effects of differential diffusion on the flame structure of oxygen enhanced turbulent non-premixed jet flames

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The ever increasing demand for power supply and environmental concerns motivate research activities in the field of alternative fuels. Such fuels mostly made from biomass, coal or natural gas have the advantage of an increased thermal efficiency, increased flame stability and reduced NOx emissions.The conversion process mostly takes place in an oxygen enhanced environment. An example for this is the partial oxidation of hydrocarbons in order to arrive at a hydrogen and carbon monoxid rich syngas mixture. All of these fuels have in common that strong and weak diffusive species coexist in the mixture. In addition to the diffusive transport the mixing process in practical flow applications is also controlled by the turbulent transport. Although Kolmogorov's theory implies that at sufficiently high Reynolds numbers differential diffusion effects should be negligible, there exist evidence that this is questionable for fuels made from biomass(e.g. syngas,DME). These effects are investigated by means of Direct Numerical Simulations of turbulent non-premixed jet flames. A turbulent jet flame is characterized by a turbulent/non-turbulent interface in the vicinity of the reaction zone. This interface strongly affects transport processes into the reaction zone which therefore have a direct influence on the flame structure. The effect of differential diffusion at the turbulent/non-turbulent interface will be addressed by conditional statistics.

Rayleigh-Taylor unstable flames: instability, turbulence and burning

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Rayleigh-Taylor (RT) unstable flames play a critical role in Type Ia supernovae because their speed and dynamics directly influence the properties of the explosion. However, RT unstable flames themselves are not well-understood. In particular, the flame speed (the rate at which fuel is consumed) is not well-known because it depends on the complex interaction of burning, the Rayleigh-Taylor instability of the flame front, and turbulence generated by the perturbed flame. In this presentation, we will present measurements of the flame speed calculated from three-dimensional direct numerical simulations of RT unstable model flames. These measured flame speeds will be used to indirectly evaluate subgrid models for the flame speed commonly used in full-star simulations of Type Ia supernovae. In particular, we will focus on the competition between burning, the RT instability and turbulence and discuss how these three processes affect the flame speed and other flame properties.

Front propagation in cellular flows for fast reaction and small diffusivity

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We investigate the influence of fluid flows on the propagation of chemical fronts arising in FKPP type models. For the cellular flows we consider, the front propagation speed can be determined numerically by solving an eigenvalue problem; this is however difficult for small molecular diffusivity and fast reaction, i.e., when the Peclet (Pe) and Damkohler (Da) numbers are large. Here, we employ a WKB approach to obtain the front speed for a broad range of Pe,Da small compared to 1 in terms of a periodic path -- an instanton -- that minimizes a certain functional, and to derive closed-form results for Da on the order of Pe and for Da small compared to Pe. Our theoretical predictions are compared with (i) numerical solutions of the eigenvalue problem and (ii) simulations of the advection--diffusion--reaction equation.

Mathematical Aspects of Non-Equilibrium Dynamics

vortex dynamics, singularities, discontinuities, asymptotic dynamics, weak solutions, well- and ill-posedness, transport out of thermodynamic equilibrium

Non-Newtonian turbulence and a generalized phase transition

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This contribution rests on a novel theory of inviscid turbulence without empirical parameters, predicting e.g. the von-Karman constant as (2 pi)^(-1/2) ~ 0.399. This is very close to the international standard value of 0.4. This theory [1] could be successfully generalized here to the case of finite Reynolds numbers and namely to non-Newtonian fluids of shear-thickening character. We show that strong mechanical forcing over small spatial scales may lead to the collapse of turbulence into locally laminar but globally still irregular motions with much less mixing efficiency and to a co-existence of laminar and turbulent regions and space and time. Energetically we differentiate between irregular and turbulent motions. The latter we define by the presence of a finite Kolmogorov (5/3 law) section in the overall power spectrum. On the low- wavenumber side it is bounded by the so-called energy-containing scale, and at the high- wavenumber end by Kolmogorov's microscale. The collapse occurs when the latter equals the so-called energy-containing scale and mixing is strongly reduced.

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"Motion" and "Fluid Flow" - conventional and modern concepts

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Motion in theoretical mechanics is defined as transport of a body of fixed mass with time with respect to some mutually motionless bodies (frames), as well as by its momentum and energy. From external decomposition of vector spaces follows that the body velocity and momentum belong to the same space. In the geometric definition the motion is a transformation of the space into itself while maintaining mutual distances and locations of the objects. Motion is decomposed on independent translation and rotations. Equivalence of all four definitions of movement allows using all the results of theoretical mechanics and applied mathematics of 3D vector spaces.

Density of fluid is variable physical quantity of dual mechanical and thermodynamic nature, fluid particle is deformable and have no physically defined boundaries. Decomposition of flow includes shear term. Physically flow is defined by its force action on submerged obstacles or by flow rate. Mathematically flow is defined as flux of momentum supplemented by self-consistent variations of thermodynamic quantities. Properties of different models of flows and complex structures of elementary flows like monochromatic waves and vortices are discussed. Some demands to experimental techniques following from condition of observability of physical quantities are presented.

The local structure of turbulent flows at high Reynolds numbers

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It is customary to analyze turbulent flows by structure functions. However, the information about the local structure of the turbulent field is lost when taking ensemble averages over fixed separation distances. This drawback may be overcome by the theory of dissipation elements, where two-point statistics are calculated along gradient trajectories that connect local minimum and local maximum points in the scalar field. The spatial region formed by the ensemble of all gradient trajectories sharing the same extreme points is called dissipation element. They may be parameterized by the linear separation distance and the scalar difference between the extreme points. By this approach the linear separation distance itself becomes an intrinsic stochastic quantity that is determined by the turbulent field. Here, we propose to decompose the signal of a passive scalar along a straight line into piece-wise monotonously increasing or decreasing line segments that start at a local minimum point and end at a local maximum point or vice versa. These line segments can be understood as one-dimensional dissipation elements and thereby we retain the property that the decomposition is determined intrinsically by the turbulent field and capture the local structure of theturbulent field. But because the decomposition is one-dimensional it can be easily related to conventional structure functions.
To examine statistics of line segments we have conducted direct numerical simulations of turbulent scalar mixing with Taylor microscale based Reynolds number varying between 85 and 530. Based on this data base, statistics and scaling laws of line segments are computed and the results are compared to conventional two-points statistics.

A path integral formalism for non-equilibrium Hamiltonian statistical systems

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A path integral formalism for non-equilibrium systems is proposed based on a manifold of quasi-equilibrium densities. A generalized Boltzmann principle is used to weight manifold paths with the exponential of a multiple of the information discrepancy of a particular manifold path with respect to full Liouvillean evolution. The likelihood of a manifold member at a particular time is termed a consistency distribution and is analogous to a quantum wavefunction. The Lagrangian here is not of Onsager-Machlup form, however at large times approaches one with the thermodynamics being of a generic Oettinger form. The proposed path integral has connections with those occurring in the quantum theory of a particle in an external electromagnetic field. It is however entirely of a Wiener form and so practical to compute. The methodology should have wide applicability in non-equilibrium turbulent systems.

Quasi-solution approach to nonlinear problems

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Typically, it is difficult to come up with an explicit solution to a nonlinear differential equation or integro-differential equation. On the other hand, numerical techniques are usually versatile enough to give solutions; the only problem is that they are usually no rigorous error bounds. We will talk about recent investigations where numerical solutions are used to construct explicit and efficient representation of solutions, which may be thought of as quasi-solution and analysis is used to control the error. In the process, one gets an solution existence proof as well. The methodology is general, though the proofs for problems with more than one variable or parameters are typically computer assisted, though not always. We illustrate this methodology on some simple well-known problems, including Navier-Stokes solution in a rectangular cavity with top boundary moving with some constant speed.

Mass transfer in drug delivery systems

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Controlled drug delivery has been attracted great attention for years as an efficient way to provide treatment of a wide class of diseases. The drug delivery systems are characterized by various physical phenomena that need an adequate quantitative description. In the present talk, we consider several physical processes relevant to drug delivery:
(i) drug transfer from a swelling polymer matrix;
(ii) dynamics of drug release from liposomes;
(iii) drug release and hydrodynamic flows in a mucus layer.

These processes, which still have been studied using simplified approaches, are investigated by means of self-consistent mathematical modeling.

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Structural instability of a subdiffusive fractional equation and its regularisation

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We show that the subdiffusive fractional equations with constant anomalous exponent in a bounded domain are not structurally stable with respect to the nonhomogeneous variations of exponent. In particular, the Gibbs-Boltzmann distribution is no longer the stationary solution of the fractional Fokker-Planck equation whatever the space variation of the exponent might be. To rectify this problem we propose the inclusion of the random death process in the random walk scheme. From this, we arrive at the modified fractional equation and analyze its asymptotic behavior, both analytically and by Monte Carlo simulation. We show that this equation is structurally stable against spatial variations of the anomalous exponent. Additionally, in the continuous limit we arrive at an advection-diffusion equation where advection and diffusion coefficients depend on both the death rate and anomalous exponent.

Experimental Investigation of the emergence of chaos in the dynamics of current sheets and flux ropes

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The solar corona is populated with thousands of magnetic flux ropes at any one time. In a laboratory experiment ropes immersed in a uniform magnetoplasma are observed to twist about themselves, writhe about each other and rotate about a central axis. They are kink unstable and smash into one another as they move. Flux ropes are also generated when a narrow sheet of current tears into magnetic islands. The islands become flux ropes. Both cases are investigated. Full three dimensional magnetic field and flows are measured at thousands of time steps. Each collision results in magnetic field line reconnection and the generation of a quasi-seperatrix layer (QSL). Three dimensional magnetic field lines are computed by conditionally averaging the data using correlation techniques. The vector potential and the plasma potential is measured everywhere in the volume with an emissive probe. This allows the determination of the total electric field and the plasma resisitivity. The permutation entropy is calculated from time series of the magnetic field, flow, potential or other data and used to calculate the Jensen Shannon complexity map. The location of data on this map indicates if the magnetic fields are stochastic, or chaotic. The complexity is a function of space and time. Other types of chaotic dynamical models such as the Lorentz, Gissinger and Henon process also fall on the map and can give a clue to the nature of the flux rope turbulence. The entropy and complexity change in space and time which reflects the change and possibly type of chaos associated with the ropes. The maps give insight as to the type of chaos and underlying dynamical process. The power spectra of much of the magnetic and flow data is exponential and Lorentzian structures in the time domain are embedded in them.

Streamline segments in turbulent flows and their statistics

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Streamlines can be considered as natural geometries of turbulent flow fields. They can be subdivided into streamline segments by taking as their ending points the locations where the absolute value of the velocity u along the streamline coordinate s has either a minimum or a maximum, i.e. the points where the projected gradient in streamline direction vanishes. Streamline segments can be sorted into positive and negative segments. They are parameterized in terms of the arclength l between two neighboring extrema and the velocity difference Δu at the extrema. Both parameters are statistical variables and streamline segments are characterized by the joint probability density function $P(l, \Delta u)$. Based on a previously formulated model for the marginal pdf of the arclength l, a model for the joint pdf is formulated. The overall properties of turbulent flows can be explained from these statistics; for instance, the negative skewness of the velocity gradient becomes a natural kinematic outcome.

Forecasting extreme events by combining observations and high-resolution numerical simulations using a Bayesian hierarchical model

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Meaningful turbulence forecasts would be useful for many applications, ranging from extreme events in Earth's atmosphere, to solar dynamics, and space-weather predictions. Nevertheless, in all of these examples (and many more) large-scale prediction models lack the resolution needed to characterize the key dynamics, which include critical smaller scale processes and the ensuing turbulence that results. As a result current subgrid-scale (SGS) parameterizations in these models are applied at much larger length scales than are appropriate, and the key dynamical processes that give rise to turbulence and transport are strongly damped. There are two ways to address this problem: 1) increase model resolution or 2) employ a probabilistic approach. We are using both methods, and as such, we have devised a Bayesian Hierarchical Model (BHM) for SGS parameterization. I will present results from this methodology applied to a mesoscale forecast model for the earthâ€™s atmosphere that 1) estimates the local likelihood of key dynamical phenomena (e.g., wind-shear instability, gravity-wave breaking, and critical level absorption) as a function of altitude from compiled balloon and aircraft data, 2) quantifies the dynamics using pre-computed high-resolution direction numerical simulations (DNS) of these processes, and 3) predicts probability density functions (PDFs) of desired SGS quantities. The beauty of the approach is that non-Kolmogorov statistics can be accurately described as long as the relevant processes are represented in the observations and the simulations. The observational data used exhibit PDFs that are non-trivial but universal, lending themselves to simple parameterization, giving vertical resolution requirements for deterministic forecast skill. Also, the high-resolution DNS of turbulent mixing layers demonstrate rich behavior that shows strong dependence on the Richardson number, facilitating detailed comparisons with aircraft data and dynamical- event census.

Cumulation effect in gas-hydraulic analogy of the shock wave

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Gas-hydraulic shock analogy [1] is used in the educational process at universities in laboratory based workshops on gas dynamics. Hydraulic jump occurring in the channel of the hydraulic model by removing the flat partition separating compartments with high and low water level, is an analogue of the stationary shock wave produced in a shock tube at the rupture of the diaphragm separating the compartments with high and low pressure in the pipe. However, at the initial stage of the flow in the hydraulic model there appears a “bulge” after the removal of the partition distorting the flow level profile in the channel. Computational and experimental study of the distortion of the flow pattern with the view to minimize it showed that it is not associated with the movement of the partition, and is due to the dynamic process of redistribution of hydrostatic pressure in the compartments of the hydraulic model at the initial stage of the flow, accompanied by the formation of a flat cumulative jet. Partition thickness variation allows to control the process to a certain extent.

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Numerical modeling of collisionless magnetized turbulence

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Turbulence plays an important role in determining the transport and heating of space, astrophysical, and laboratory plasmas. Modeling this turbulence is particularly challenging because of the self-generated electromagnetic fields associated with moving charges, the ability of the plasma to support waves with disparate space-time scales, and the fact that a kinetic treatment is sometime required. Numerical simulation is a necessary and effective tool in understanding and learning how to minimize turbulence in magnetically confined fusion devices. By exploring different computational methods, we can develop the more efficient and experimentally relevant simulations that will allow scientists to test hypotheses prior to implementing them in multi-billion dollar fusion experiments such as ITER. This work will compare the effectiveness of various computational methods, including spectral methods and the discontinuous Galerkin method, in simulating simple turbulence models. I will address topics such as stability, efficiency, and relevance of such simulations to current theory and experimental observations.

Spectral modelling of unstably homogeneous stratified turbulence

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We model unconfined homogeneous turbulence with destabilizing background density gradient in the Boussinesq approximation [1]. Starting from initial isotropic turbulence state, the buoyancy force injects energy in the flow leading to a strong growth of kinetic energy, and to anisotropic structures. The corresponding dynamics is difficult to reproduce using one-point turbulent models, so that we introduce an anisotropic two-point statistical model of the eddy-damped quasi-normal markovian (EDQNM) kind [2], that includes buoyancy production. The model is compared to results of direct numerical simulations at various values of initial Froude number and kinetic to potential energy ratios. We show that the characteristic relaxation time for triple correlations in the EDQNM closure has to include an explicit correction due to stratification in order to match numerical simulation results. In that case, the anisotropy of velocity and scalar fields as well as the spectral energy distributions are also in very good agreement with DNS results.

[1] O. Soulard, J. Griffond, B.J. Grea, Phys. Fluids, 65, 015110, 2014; [2] F. S. Godeferd, C. Cambon, Phys. Fluids, 6, 2084-2100, 1994; [3] J.J. Stoker, Mathematical Theory and Applications . Moscow: Izd. Lit. , 1959.

The influence of confinement shape on the scaling of turbulent fluctuations in convection

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We perform numerical simulations of turbulent convection confined into a cubic enclosure for Rayleigh numbers Ra from 10^6 to 10^{10} and at a fixed molecular Prandtl number Pr of 0.7. Large eddy simulations (LES) were carried out using a second order accurate finite difference method, where both subgrid-scale momentum and heat fluxes were parametrized using a Lagrangian dynamic Smagorinsky model. We measure the time-averaged spatial distributions of both the local heat flux and density fluctuations. For a square horizontal cross-section these quantities are inhomogeneous in the horizontal mid-plane under conditions of statistical stationarity, lacking the rotational symmetry characteristic of the more typical cylindrical cross-sections.

Numerical simulation of vortex cascade of instabilities in shear layers

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We investigate initial stage of the onset of the turbulence in 3D free shear flow of an ideal compressible gas with (Kholmogorov's problem) and without constant external force. The onset and development of the vortex cascade of hydrodynamic instabilities were traced by the direct simulation of the classical laws of conservation without the influence of viscosity and walls: Euler's equations in case of shear layer and Euler's equations with right side in case of Kholmogorov's problem. For numerical simulation we used monotonic dissipative stable finite-difference scheme with positive operator. In this work we consider initial stage of the onset of the turbulence for both problems. It is shown that in case of a problem without affecting the constant force of the vortex cascade develops as follows: the evolution of the flow at the beginning demonstrates a quasi-two-dimensional nature (the onset of instability begins with the formation of large-scale vortex). However, evolving further, the large-scale vortex changes its shape with time and finally gets destroyed. Formation of the vortex cascade in Kolmogorov's problem is following. In contrast to the shear layer, the flow loses its stability due to instabilities in the form of a comb across the excited surface. Over time, this comb is stretched due to the formation of new instabilities. Large structure is formed implicitly. This structure finally also gets destroyed. It leads to the collapse into smaller vortexes. Thus, in this case the vortex cascade is also exist. Direct numerical simulation shows that the transition to chaos occurs through an eddy cascade of instabilities, which corresponds to the Richardson-Kolmogorov-Obukhov energy cascade. Decomposition of kinetic energy on wave number reveals correspondence with the energy spectrum of Kolmogorov-Obukhov and negative five thirds low.

Universality of small scale statistics of passive scalar in turbulence

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Recent experiments and Direct Numerical Simulations (DNSs) have found facts to suggest that the universality of small scale statistics of passive scalar may not be as "universal" as in the velocity case. To address the above issues, we study the moments of scalar increment in steady turbulence at the Taylor microscale Reynolds number higher than 800 by using DNS up to the grid points of 4096x4096x4096. In order for the scalar and turbulent flow to be as ideal, faithful and honest as possible to the assumptions that would be made in theories, we set DNS in such a way that Scalar 1 and Scalar 2 with Sc=0.72, where Sc is the Schumidt number the ratio of the molecular viscosity to the molecular diffusivity, are simultaneously convected by the identical isotropic turbulent flow but excited by two different methods. Scalar 1 is excited by the random scalar injection that is isotropic, Gaussian and white in time at low wavenumber band, while Scalar 2 is excited by the uniform mean scalar gradient. The moments of two scalars are computed as the functions of the separation vector and then expanded in terms of the Legendre polynomials. This enables us to extract the scaling exponents of the structure functions in the various anisotropic for Scalar 2. We have computed the local scaling exponents as function of the separation distance in order to examine the degree of the universality of the exponents. Our findings are that the exponents of the isotropic sectors seem to have the same values at separation distances in the narrow range over which the 4/3 law holds simultaneously for two scalars. The exponents of the anisotropic sectors and the cumulants of the moments will also be reported.

Perturbation theory and numerical modeling of weakly and moderately nonlinear dynamics of the incompressible Richtmyer-Meshkov instability

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A study of incompressible two-dimensional (2D) Richtmyer-Meshkov instability (RMI) by means of high-order perturbation theory and numerical simulations is reported. Nonlinear corrections to the Richtmyer's impulsive formula for the RMI bubble and spike growth rates have been calculated for arbitrary Atwood number, and an explicit formula has been obtained for it in the Boussinesq limit. Conditions for early-time acceleration and deceleration of the bubble and the spike have been elucidated. Theoretical time histories of the interface curvature at the bubble and spike tip, the profiles of vertical and horizontal velocities have been calculated and favorably compared to simulation results. In our simulations we have solved 2D unsteady Navier-Stokes equations for immiscible incompressible fluids using the finite volume fractional step flow solver NGA developed by Desjardins et al. 2008 coupled to the level set based interface solver LIT (Herrmann 2008). We study the impact of small amounts of viscosity on the flow dynamics and compare the simulation results to the theory to discuss the influence of the theory's ideal inviscid flow assumption.

Schmidt and Prandtl number dependence of RT mixing at large Reynolds number

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The late time, high Reynolds number mixing in Rayleigh-Taylor flows is believed to be self-similar with a quadratic growth law. The growth rate, alpha, is systematically underestimated in numerical treatments vs experiments [1]. Some believe this is due to misrepresentation of molecular diffusion due to dissipative truncation errors. We present new simulations using the spectral element method in the NEK5000 code, which has exactly zero numerical dissipation. We focus on the dependence of the flow on the Schmidt or Prandtl numbers, which are well defined in this method, as route to understanding the importance of molecular diffusion on late-time behavior.

[1] G. Dimonte, et al., Phys. Fluids 16, 1668 (2004).

Mixing in phase-space due to the two-stream and filamentation instabilities of ion and electron beams propagating in background plasma

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Intense electron or ion beams propagating in plasmas are subject to the two-stream and filamentation instabilities, which lead to a slowing down of the beam particles, acceleration of the plasma particles, and transfer of the beam energy to the plasma particles and wave excitation. Making use of the particle-in-cell codes EDIPIC and LSP, we have simulated two-stream instability interactions over a wide range of beam and plasma parameters. Typically, the instability saturates due to nonlinear wave-trapping effects of either the beam particles or plasma electrons. The saturation due to nonlinear wave-trapping effects limits the "mixing" in phase-space and may produce coherent structures in the electron velocity distribution function. For the case of an electron beam, simulations show that the two-stream instability is intermittent, with quiet and active periods. During the active periods of the two-stream instability, the beam interacts with the plasma most intensively at locations where the global frequency of the instability matches the local electron plasma frequency. These intense localized plasma oscillations produce peaks in the velocity distribution function similar to the ones measured in the experiment. For filamentation instability, filaments form coherent structures in phase space that can survive for long time and limit mixing in phase space or heating.

Turbulence and mixing layers in Rayleigh-Taylor instability

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We study mixing layers generated by Rayleigh-Taylor instability. Compressible model being very costly, we focus on anelastic and Boussinesq models which have been established through asymptotic analysis. The fomer offers a way to study slightly stratified RT mixing layers within an incompressible-like framework where acoustic waves are filtered out. The latter is only valid for vanishing Atwood number and no stratification. Anelastic approximation contains a degree of freedom, the mean density, such that the product of the mean density and the velocity is divergenceless. We discuss the choice of mean density. Time-varying mean density seems to be excluded. Initial state and final state are two potentially good candidates. The former leads to non-physical mass flux in the midplane but the latter exhibits good behavior. Our simulation tool, Amenophis, is based on a pseudo-spectral auto-adaptive Chebyshev multidomain method. It contains three physical models: compressible, anelastic and Boussinesq. The last two have been developed recently. We describe the high-order numerical method for solving the anelastic and Boussinesq equations with spectral accuracy. Concentration, temperature and one component of velocity are solved as Helmholtz equations, while pressure and the last two components of velocity are solved with an Uzawa method. Both direct and iterative solvers were developed. A 2D-parametric study in Atwood number demonstrates good agreement between compressible, anelastic and Boussinesq models. We also show results from large-scale 3D numerical simulations. Turbulence characteristics are detailed. Structures and properties of the compressible, anelastic and Boussinesq 3D flows are compared.

[1] Schneider N. & Gauthier S. 2014 (submitted); [2] Schneider N. et al 2014 (in preparation)

Instability of a planar detonation front in condensed-phase explosives: from laminar to turbulent detonation via a cellular detonation regime

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The classic Zel'dovich, von Neumann, and Doering (ZND) theory is successfully used to calculate the detonation speed in both gas- and condensed-phase explosives. ZND theory assumes a laminar one-dimensional detonation with a planar front. However, experiments demonstrate that a gas-phase detonation can exhibit non-planar structures corresponding to cellular, spinning, and pulsating-turbulent detonation regimes. In contrast to gases, such structures have yet to be observed experimentally in condensed-phase explosives. The structure of a self-sustained detonation wave in a solid represented by a reactive AB model is studied using molecular dynamics (MD) simulations. Parameters of the AB model are modified to investigate the stability of the detonation front assuming different barrier heights for the exothermic chemical reaction driving the detonation. It is shown that for barriers below 0.2 eV the detonation front remains planar and material flow is laminar irrespective of the sample cross-section. For higher barriers, the planar detonation front becomes unstable in a channel with large enough width. The initially laminar detonation transforms into a two-dimensional cellular pattern having a pulsating front structure with dynamical hot spots/heads such as Mach stems and transverse shocks, where reactions are initiated. In round tubes with small enough radii a single-headed spinning detonation is observed with a ratio of helical pitch to tube diameter in agreement with gas-phase experiments. The number of detonation heads increases linearly with increasing tube cross-section eventually leading to a multi-headed turbulent-like detonation due to collisions between heads. Although at a much smaller scale, the various regimes of detonation observed in the MD simulations mirror regimes of detonation observed in gasses, consistent with a universal hydrodynamics mechanism guiding the formation of detonation patterns.

Numerical and experimental study of the unsteady flow visualization method using polystyrene markers

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High-quality data visualization remains a challenge in experimental study of hydrodynamic flows even after more than a century of its development pioneered by Osborne Reynolds in 1883. This paper presents the results of analytical, numerical and experimental study of the unsteady flow using spherical markers for its visualization. Markers are made of polystyrene, a material which density is close to the water density. Flow visualization results obtained using these markers are given in detailed comparison with the results of other flow visualization methods. We analyze the influence of the following sources of error on the hydrodynamic flow velocity measurements:

- desynchronization between the fluid motion and the motion of the markers immersed in the fluid caused by the density difference between polystyrene and water, viscous resistance and finite markers' size;
- the influence of gravity.

Based on the obtained results we discuss the role of smoke particles in the experimental study [1] of turbulent mixing zone at the boundary between air and helium accelerated by shock waves.

[1] Meshkov et. al., Combust.Explosions ShockWaves, 26, 315-320 (doi:10.1007/BF00751371) (1990)

The application of the overhead projection method for the microparticles optical detection

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In experiments on the instability of the condensed medium free boundary, accelerated by the shock wave, a microparticles cloud is formed (e.g. [1]). To register microparticles and measuring their dimensions the optical detection method [2], based on the overhead projection scheme can be applied. In this method, a light source, a micro-object, an image photodetector (a photographic material, a CCD or CMOS sensor) and a lens are sequentially disposed on the same optical axis, while the registered object (for example, a microparticle or a cloud of microparticles) is placed in front of

the lens in the interval from one to two focal lengths and the photodetector is placed in the conjugate plane at a distance from the lens. In this case, an enlarged view of microparticles is formed in the projection plane. The powerful directional light source (such as a pulsed laser with very short light) in such a system provides the enough frame illumination to produce an image of moving particles having speed 1 kilometer per second and more with a short exposure.

[1] M.V. Astashkin et. al., JETP Letters, Vol. 99, No. 3, pp. 146â€“148 (2014); [2] Y.B. Bazarov, Ð•.Ð•. Meshkov, Patent RF for useful model, No. 107379 (2011)

Flow and grow: simultaneous global measurement of velocity fields and reaction fronts

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A central challenge in advancing the theory and application of advection-reaction-diffusion science is the need for datasets that include both velocity and reaction state, across the system, at high resolution, as they evolve in time. Such datasets are large and particularly difficult to obtain in experimental studies, where making individual measurements would require a huge number of probes and would likely interfere with the processes being measured. My group and I have developed methods for simultaneous global measurement of velocity fields and reaction fronts in laboratory advection-reaction-diffusion experiments. With two high-resolution cameras we can track particles, track reaction fronts, and align the two types of data in both space and time. I will describe the system and its use as a model for the mixing and growth of oceanic phytoplankton, a complex biogeophysical system essential to climate stability.

Diagnosing Hot-Spot Mix with X-Ray Spectroscopy

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X-ray spectroscopy of tracer elements provides a mix diagnostic for ignition-scale targets at the National Ignition Facility. The stagnated implosion has a central hot-spot region surrounded by a cold and dense compressed shell. The deuterium-tritium hot spot has an electron temperature in the 2- to 4-keV range and an electron density of about 10^{25} cm^{-3}, while the compressed shell is several times denser and cooler. The compressed shell is comprised of an outer layer of plastic doped with trace amounts of copper and germanium and an inner layer of deuterium-tritium fuel. Hydrodynamic instabilities mix material from the outer layers into the hot spot. The amount of hot-spot mix mass is determined from the absolute brightness of the copper and germanium K-shell emission. The copper and germanium dopants placed at different radial locations in the plastic ablator show the ablation-front Rayleigh-Taylor hydrodynamic instability is primarily responsible for hot-spot mix. Low neutron yields and hot-spot mix mass between 30 and 4000 ng are observed [1].

[1] S. P. Regan et al., Phys. Rev. Lett. 111, 045001 (2013). This material is based upon work supported by the Department of Energy National Nuclear Security Administration under Award Number DE-NA0001944, the University of Rochester, and the New York State Energy Research and Development Authority. The support of DOE does not constitute an endorsement by DOE of the views expressed in this article.

Probing the interface between a plasma jet and an ambient plasma

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Intense, collisionless flows are generated using a laser-target interaction (10^{11} W/cm^2). The flow speeds are supersonic to Alfvenic and are directed parallel to the confining magnetic field of a large, ambient plasma. The entire experiment is operated at a one-second cadence, allowing the acquisition of ensemble sets of data. The plasma-jet interaction is measured directly with probes, revealing the time-varying electrostatic and magnetic fields involved. The deposition of energy by the laser initiates a dynamic sequence of events as the laser-produced plasma expands and transfers energy to the background plasma. The laser plasma initially expands with strong density gradients, producing a diamagnetic cavity with a radius of several ion Larmor radii in the background plasma. Plasma instabilities which grow on the gradients collapse the cavity on timescales much shorter than expected from magnetic diffusion. A fraction of fast ions decouple from the cavity and are observed to remain as a collimated jet several ion inertial lengths along the ambient magnetic field. Although the ion-ion collision length is much longer than the size of the experimental device, the expanding jet expels ambient ions, carving out a density channel. This channel is revealed using the technique of laser-induced fluorescence on the ambient argon ions with an atomic transition distinct from the expanding carbon ions. These measurements, along with a three-dimensional reconstruction of the electric and magnetic fields and their turbulent fluctuations during the initial jet expansion will be presented.

These experiments are conducted in the Large Plasma Device at UCLAâ€™s Basic Plasma Science Facility and is jointly funded by the U.S. DoE and NSF.

Understanding biolocomotion in fluids: swimming and flying

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Flying birds and swimming fish are familiar sights to everyone, but their remarkable locomoting mechanisms are often poorly understood. Inspired by these examples, we investigate experimentally the interactions between unsteady flows and dynamic boundaries (here flapping wings or fins). In one experiment, we study the functional origin of flapping flight and also investigate how finite flexibility of a wing determines the flight speed and even the flight direction. In another experiment, we investigate the group dynamics of multiple locomotors as they interact with each other through the passing flows. These experiments have offered a few surprises.

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