Relativistic Hydrodynamics: Theory and Modern Applications

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Relativistic hydrodynamics and heavy-ion collisions

The resurgence of interest in RH stems from the spectacular success of the hydrodynamic description of the Quark-Gluon Plasma (QGP) created in high-energy nuclear collisions. RH has become a paradigm of heavy-ion phenomenology. Analytical work is being accompanied by development of numerical codes describing the data from SPS, RHIC, and LHC experiments. The observed hydrodynamic phenomena such as anisotropic flow in nuclear collisions motivated theoretical scrutiny of causal dissipative RH and the classification of transport coefficients beyond the first order (Navier-Stokes) in the gradient expansion. The rich data on event-by-event fluctuations, such as higher harmonics of flow, together with the new theoretical tools should help us pin down the values of important transport coefficients of the QGP and their temperature dependence. RHIC has recently completed the first stage of the Beam Energy Scan (BES-I) with interesting, yet inconclusive results indicating the possibility of observing the QCD critical point and the onset of the first-order phase transition to the QGP at higher baryon densities. The second stage, BES-II is planned for 2018. This motivates a concerted theoretical effort aimed at developing the RH description of QCD matter in the regime where a non-vanishing baryon current is important and where the critical phenomena and physics of anomalies need to be incorporated into the RH context.

Anomalous chiral effects

The role of quantum anomalies in RH has been a major subject of recent theoretical work. The possibility of experimentally observing anomalous non-dissipative currents in the QGP motivates the theoretical investigation of such currents. Colliding ions create considerable magnetic fields. As a result, the Chiral Magnetic Effect (CME) can translate fluctuations of net chirality, which could be driven by topological (sphaleron) transitions in the QGP, into observable fluctuations of the charge asymmetry with respect to the reaction plane. Recently, RHIC experiments reported the experimental observation of charge-asymmetry fluctuations, later confirmed at LHC, as well as the expected disappearance of this effect at low collision energies where the energy density of created matter is smaller and likely below the critical one needed for the restoration of chiral symmetry. Closely related phenomena have been discussed in the physics of neutrinos, primordial electroweak plasmas, and quantum wires. The chiral vortical effect (CVE) which could, for example, lead to the asymmetric neutrino emission from a rotating star or a black hole has received considerable attention due to its intriguing connections to gravitational anomalies. Furthermore, the possible observation of particle polarization related to these effects and to general vorticular flows has been discussed in recent literature.

Foundations of relativistic hydrodynamics

As a natural consequence of the renewed interest in RH, fundamental questions have arisen about the foundations of relativistic hydrodynamics. Should RH be seen as derivable from kinetic theory or as a more fundamental consequence of quantum field theory and gravity? The most widely known formulation of RH relies on the existence of an entropy current four-vector. Is this necessary? Can one show that RH is uniquely defined in equilibrium as well as in non-equilibrium situations? Are all hydrodynamic frames (e.g. Landau and Eckart) equivalent from the point of view of stability and causality of the equations of motion? Does the presence of a fundamental spin tensor play a role? These are only some of the interesting fundamental questions recently posed in the context of RH that could be discussed in the program.

Relativistic hydrodynamics and AdS/CFT correspondence

The AdS/CFT correspondence, and more general gauge/gravity dualities, can be used to study relativistic strongly interacting systems in a hydrodynamic regime. Such systems include the QGP, neutron stars, and also certain condensed matter systems (with a relativistic effective field theory description). AdS/CFT has already had an enormous impact on RH. The universal viscosity to entropy density ratio of AdS/CFT models has triggered discussions about the viscosity of hydrodynamic systems such as cold atoms and the QGP. AdS/CFT has also provided computable models of out-of-equilibrium and anisotropic plasmas, models which provide insight into the time-evolution of the QGP formed at RHIC and LHC. It has also served as a convenient framework for understanding effects of anomalies in hydrodynamics. AdS/CFT continues to be an active field of research with possible developments in RH related to turbulence, external electromagnetic fields, superfluids, and generalized forms of the gradient expansion.

Relativistic hydrodynamics in astrophysics

To date, state-of-the-art modeling of a wide spectrum of high-energy astrophysical phenomena include (general) relativistic hydrodynamics or magneto-hydrodynamics (MHD): from the structure of accretion onto compact objects, to the boosting of jets from extragalactic sources, from pulsar winds and associated nebulae, to the evolution of the fireballs responsible for Gamma Ray Burst emission. Because of the complexity and non-linearity of the equations, substantial progress in this field has been made only recently, owing to the improvement in the numerical techniques and supercomputer technologies. Nowadays numerical relativity is so advanced that even the fluid and MHD evolution of self-gravitating objects can be followed by solving the Einstein equations at each time step of fluid evolution, and thus predicting the emission of gravitational waves, e.g. from mergers of binary neutron stars or black holes. The next frontier is probably the self-consistent addition, in a general relativistic framework, of non-ideal effects, such as viscosity, resistivity, and radiative emission, so as to be able to directly compare extremely realistic simulations with the observational data, and gain further insight in the physics of these fascinating astrophysical sources. In this respect, we believe that an interaction between the astrophysics and the relativistic heavy-ion communities will be very fruitful.