Shocks and sounds in Quark-Gluon Plasma

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Abstract

Large energy deposition from LHC quenching jets restarted interest to shock formation. Shocks also have theoretical significance as the simplest out-of-equilibrium setting without time dependence. While weak shocks have small gradients and can be treated hydrodynamically in the Navier-Stokes (NS) approximation, the ones without a small parameter (strong shocks) needs other methods. Two of those will be applied: (i) the "resummed hydrodynamics" proposed earlier by Lublinsky and myself; and (ii) AdS/CFT correspondence, which uses the gravitational setting. In the latter case we apply novel variational approach and find approximate solution. The conclusion from both treatments is that the strong shocks deviate from NS only be few percent. We then propose a novel mechanism of shock production at hadronization, from Raileigh collapse of the QGP bubbles. Further discussion of the "fireball sonograms" deals with shocks/sounds produced by the quenching jets.

Keywords: QGP, hydrodynamics, equilibration, AdS/CFT

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1. Strong shocks in AdS/CFT [1]

The shocks are jumps from one state of matter to the other, and thus they are important methodically, for the understanding of the main unsolved problem of the field, a very rapid equilibration of sQGP. *Weak shocks* are small jumps across the wide fronts, those are basically sounds which are parametrically well described by hydrodynamics. *Strong shocks* are jumps $O(1)$ and their shape/width is the issue we study. In gases, amenable to kinetic treatment, this width is defined by the particles' mean free paths. In liquids, of which sQGP is one, the width is defined by gradient expansions and viscosities.

In the frame comoving with a shock there is no time dependence. The fluxes of momentum and energy T_{11}, T_{01} are simply constant, so in the Navier-Stokes (NS) approximation for relativistic fluid one has

$$(\epsilon + p)u_1^2 + p + \eta\frac{4}{3}\partial_x u_1 + O(\partial^2) = C_{11}; \quad (\epsilon + p)u_0 u_1 + \eta\partial_x u_0 + O(\partial^2) = C_{10} \tag{1}$$

where $u_0 = cosh(y(x)), u_1 = sinh(y(x))$ are expressed via the rapidity of the flow, η is the shear viscosity and two constants in the r.h.s. can be inferred e.g. from flows (fluxes) far before/after the shock, at $x \to \pm\infty$, where the matter is homogeneous and the gradient terms vanish. It is not hard to solve these equations for $p(x), y(x)$ and obtain the shock profile in the NS approximation. The question is how to include higher gradient terms. While not being small for strong shocks, their contribution is controlled by the coefficients – "higher viscosities" – and may or may be small.

One approach to related problems is the so called "improved hydrodynamics" suggested by Lublinsky and myself [2] (LS) which proposed a particular approximate resummation of all high gradient terms deduced from the AdS/CFT stress tensor correlators. Based on sign-alternating nature of higher viscosities, the resumption put the gradients in the denominator, like in charge screening problem. Its simplest form (called model 2 in [2]) is an operator $[1-\partial_x^2/(8\pi^2T^2)]^{-1}$. Applying LS hydrodynamics to shock problem one comfortably finds corrections to NS profile of only a percent magnitude, even for strong shocks.

However, LS is an approximation and one still would like to have the first-principle solution of this *out-of-equilibrium* problem, which the AdS/CFT correspondence provides. It means solving a very complex gravitational problem of colliding black branes. While those are notoriously difficult, the shock setting has a distinction of having a *stationary* (time-independent) setting. It is impossible to describe it here – the corresponding Einstein equations take many pages and turned out to be too long even in the full-size PRC article. Let me only state here that the method used is an (original) variational approach using elliptic nature of the Einstein equations in this setting.

The main lesson from that is that while the NS profile needs to be corrected by higher gradients, those are small O(few percents). Small viscosity $\eta/s = 1/4\pi$ plus *good convergence of series over higher viscosities/gradients* do lead to thin width of the shock, $O(1/\pi T)$, confirming rapid transition between two very different states of sQGP.

2. Mini-Bangs from Rayleigh collapse of the QGP bubbles?

The fluctuations of the initial conditions result in event-by-event fluctuations of the second (elliptic) [3] and of the higher [4] flow harmonics. At the previous QM2011 we had presented our first predictions for higher moments [6] which at this conference became a large industry. Their good agreement with RHIC and LHC data confirmed that, in spite of dissipative effects during their propagation $\tau_{freezeout} \sim 10\, fm/c$, they still have an observable magnitude. One may ask if there can be other sources of the shocks/sounds *during* the evolution. Indeed, the fluctuation-dussipation theorem insists that fluctuations in matter should appear at any time. As a particular example we now propose a new idea [7], the collapse of the QGP bubbles. As everyone knows, a coffee pot "sings" just before boiling, and we suggest that the sQGP does the same.

There are many examples that dissipation – and thus fluctuations – peak at T_c. While the QCD phase transition is a cross-over, it is close to the 1st order one, and formation of some inhomogeneous intermediate state in the near-T_c domain is probable. If so, the following sequence of events has to follow: (i) the surface tension should lead to near-spherical "QGP drops", (ii) as the temperature gets a bit below T_c they undergo the so called *Rayleigh collapse* (iii) quite efficiently transferring their energy into the outgoing shocks.

Historically, lord Rayleigh discovered collapse of the bubbles investigating demand from British navy during the World War I, on the origin of mysterious small holes in ship's propellers. About a decade ago the phenomenon has been studied extensively in the lab, in connection with the so called *sonoluminescence*. Indeed, weak sound can induce bubble collapse, in volume by a factor $\sim 10^6$, producing temperatures $O(eV)$ (thus light) and supersonic shocks with high pressures easily capable to destroy the best steel of the ship's propellers.

One can use hydrodynamics to derive the following equation for the bubble radius $R(t)$ and its time derivatives (dots)

$$\ddot{R}R + (3/2)\dot{R}^2 = \delta p_{volume} + \delta p_{surface} - \frac{4\eta\dot{R}}{\rho R} + \delta p_{sound\,radiation} \tag{2}$$

where the r.h.s. contains two effective pressures, the NS term and the sound radiation reaction term (containing higher time derivatives of R). If all these terms are neglected, the equation leads to the analytic Rayleigh's solution producing infinite velocity at certain time. As our studies found, a sufficient viscosity does stop the Rayleigh collapse. In any case, rather sudden stop of inward flow leads to the outgoing shocks, the "mini-bang" as we call them in this paper.

Finding observable consequences of those events is not simple. First of all, being produced at $T \approx T_c$, these shocks/sounds have to propagate in hadronic phase: we thus think that LHC conditions have better chance to see them than those at RHIC due to later kinetic freezeout. Second, they propagate much shorter time than those from initial perturbations, of few fm/c only, and thus much have size much smaller than "sound circles" from the initial state fluctuations (studied before). Preliminary estimates show that it is hard to see them in ϕ harmonics as they get hidden in a peak near zero relative ϕ.

We thus propose a novel approach, focusing at the correlation functions in the *rapidity* direction. Unlike the initial state perturbations, which are rapidity independent, the "mini-bangs" at T_c are born well localized in particular rapidity of the QGP bubbles.

Rapidity correlations in pp collisions are known to reveal "clusters" of certain size, decaying isotropically in their rest frame. RHIC data on AA collisions (especially from PHOBOS [8]) show clusters with larger multiplicity. Even more importantly, they have larger extension in rapidity than isotropic decays would give. Furthermore, at Hard Probes 2012 and this meeting ALICE reported appearence of a double-hump structure in rapidity correlation function, provided secondaries with few GeV p_t are selected. We suggest that those phenonemna are due to propagation of shocks/sounds in the rapidity direction. We are currently trying to describe those quantitatively, by a model including the sounds from the "mini-bangs". Complexity of the problem is related to the fact that sounds near the fireball edge are strongly distorted by radial flow, and also are sensitive to the shape of the freeze out surface.

3. Shocks and sounds from quenching jets

Sound emission from quenching jets [5] has been proposed in 2004 as an explanation of the peaks in the two-particle correlation functions at $\phi = \pi \pm 1 rad$. However it since turned out that the data used, at $p_t \sim 3\,GeV$, were unrelated to jets but are instead well explained by the hydrodynamical response to the initial state fluctuations. Of course, setting the trigger momentum higher, e.g. $p_t \sim 10\,GeV$, one goes to the domain dominated by jets. And we still maintain that certain energy deposited into matter by trigger and associate jets should go to 4 peaks at $\phi = \pm 1, \pi \pm 1 rad$, visible provided the associate particle has $p_t \sim 3\,GeV$, optimal to see higher hydro harmonics. While at RHIC those are obscured by "punch- through" associate jets, at LHC preliminary indications from ALICE (private communications) finds rather empty $\phi \approx \pi$ region and even some indication for the four peaks.

A striking phenomenon discovered at LHC is existence of very asymmetric events, in which the trigger jet has the transverse energy E_T significantly larger than that of the associate jet E_A. Energy of the jet is deposited into QGP can be as large as $\Delta E \approx E_T - E_A \sim 100\,GeV$. (The first equality we write as approximate since the trigger also looses certain energy, as well as picking up some from fluctuations/trigger bias, both O(10 GeV) or so.)

My two comments on that [9] are as follows. First: in this case one has so-to-say two underlying events. The inside of the Mach cones is the place where ΔE is dissipated. It increases T and hydro flow by few percents, which should be visible even on event-by-event basis in spectra of secondaries with $p_t \sim 3\,GeV$.

The second comment is that such energy deposition does not lead to sounds but to shocks. As the volume in which this energy is deposited is

$$V = L\pi r^2 \sim (10fm) * 3.14 * (0.36\,fm^2) \approx 10fm^3 \tag{3}$$

and its deposited energy is as above, extra energy density $\delta\epsilon \approx 10\,GeV/fm^3$ is comparable to the QGP stress in the bulk. Thus such strong quenching events should create *strong shocks*. Their velocity, known from QGP thermodynamics [1] exceeds the speed of sound, which leads to interesting and predictable dependence of the size/shape of the "heated region" on the deposited energy.

We are not currently working on modeling shocks, but sounds, as there is well developed analytic solution for those, as perturbations of the "Gubser flow" solution. Those allow to obtain Mach cone solutions, including the transverse flow and realistic viscosity.

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