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Linearized hydrodynamics from probe-sources in the gauge–string duality

Steven S. Gubser [a,*], Amos Yarom [b]

[a] *Joseph Henry Laboratories, Princeton University, Princeton, NJ 08544, USA*
[b] *Ludwig-Maximilians-Universität, Department für Physik, Theresienstrasse 37, 80333 München, Germany*

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Abstract

We study the response of an infinite, asymptotically static $\mathcal{N}=4$ plasma to a generic localized source in the probe approximation. At large distances, the energy–momentum tensor of the plasma includes a term which satisfies the constitutive relations of linearized hydrodynamics, but it can also include a non-hydrodynamical term which contributes at the same order as viscous corrections, or even at leading order in some cases. The conditions for the appearance of a laminar wake far behind the source and its relevance for phenomenological models used to explain di-hadron correlations are discussed. We also consider the energy–momentum tensor near the source, where the hydrodynamical approximation can be expected to break down. Our analysis encompasses a wide range of sources which are localized in the bulk of AdS, including trailing strings, mesonic and baryonic configurations of strings, and point particles.

1. Motivation

As a parton moves through a quark–gluon plasma, it loses energy to the medium. It is interesting to ask where this energy goes. At sufficiently large length scales, the main channels available are hydrodynamical. There are two different hydrodynamical modes. One is sound. Assuming the parton is moving at a speed v greater than the speed of sound c_s, the signature of energy loss into the sound mode is a sonic boom. The other mode is dispersive, having to do with the formation of laminar wakes (or diffusion wakes—we will not attempt to draw a distinction between

* Corresponding author.
E-mail addresses: ssgubser@princeton.edu (S.S. Gubser), yarom@theorie.physik.uni-muenchen.de (A. Yarom).

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them). Neglecting effects related to the expansion or other collective flows of the medium, the laminar wake is a stream of fluid behind the parton, moving in the same direction as the parton. Once the plasma hadronizes, we can expect that a sonic boom will lead to enhanced particle production at the Mach angle $\theta = \cos^{-1} c_s/v$, while a hadronized wake will lead to intensified particle production in the direction of the parton's motion [1,2].

Evidence for such effects may be obtained from histograms of the azimuthal angle between pairs of energetic hadrons produced in heavy ion collisions [3,4]. In [3] it was observed that for certain momenta the two-point correlation function between jets emitted from the plasma is peaked at an azimuthal angle of roughly $\pi \pm 1.2$ radians and has a minimum at π radians. This is described as "jet-splitting". Jet-splitting is suggestive of a sonic boom: a standard interpretation is that one energetic hadron (the "trigger" or "near-side" hadron) came from a hard parton that exited the plasma without losing much energy, and the other one (the "associated" or "away-side" hadron) was produced from the sonic boom caused by another hard parton whose momentum was opposite the first, at least in azimuthal angle. In [4], with more inclusive momentum cuts (and also the greater rapidity acceptance characteristic of STAR), instead of jet-splitting, a broad peak was found, centered around π.[1]

It is challenging to make an unambiguous connection between these results and hydrodynamics, but there are several notable efforts. For example, in [2] it was shown, using a hydrodynamical model and Cooper–Frye hadronization, that jet-splitting does not occur unless the diffusion wake is suppressed relative to the sonic boom; and in [6], jet-splitting, in approximate agreement with PHENIX di-hadron correlators, was predicted using a model where three quarters of the energy goes into the sonic boom. The discussion so far is anything but an exhaustive account of either the experimental or the theoretical literature on medium-induced modifications of jet structure. Recent brief discussions can be found in [7,8], while a broader treatment with more extensive references is included in [9].

In both [2] and in [6] the authors have tuned the relative amount of energy going into sound modes and diffusion modes by hand. Indeed, it is challenging to predict from QCD the relative strength of the sonic boom and the diffusion wake produced by a hard parton—assuming, of course, that sonic booms and diffusion wakes are the right language for describing the energy loss at length scales significantly larger than 1 fm. The essential difficulty is in connecting the short-distance physics, which is perturbative (or at least partly perturbative) and the long-distance hydrodynamical regime. It might therefore be enlightening to consider similar phenomena in $\mathcal{N} = 4$ super-Yang–Mills theory, where the methods of the gauge–string duality [10–12] allow detailed calculations which become reliable in the large N, large $g_{\mathrm{YM}}^2 N$ limit. Indeed, a number of papers [13–19] are devoted to studying the sonic boom and diffusion wake produced by the trailing string of [20,21], which represents a heavy quark moving at constant velocity through a thermal medium of $\mathcal{N} = 4$ gauge theory. A strong diffusion wake is predicted in these works, similar to "scenario 1" of [2], which led to no jet-splitting after Cooper–Frye hadronization. On the other hand, in [22], we showed that the leading small momentum asymptotics of a string configuration representing a heavy-quark meson, as described in [23,24], exhibit a pole structure associated with a sonic boom but no diffusion wake pole.

The aim of this paper is to get a stronger foothold on the hydrodynamic behavior of the $\mathcal{N} = 4$ plasma due to a generic probe source, with an eye toward the phenomenologically inter-

[1] A recent analysis [5] of STAR data using three-point functions exhibits a triple peak structure, where a central peak at $\Delta\phi_1 = \Delta\phi_2 = \pi$ is accompanied by two peaks of equal heights at $\Delta\phi_1 \approx \pi \pm 1.4$ and $\Delta\phi_2 \approx \pi \mp 1.4$. These latter two peaks are consistent with a sonic boom, while the central peak may be evidence for a diffusion wake.