Is there a Sonic Boom in the Little Bang at RHIC?

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The use of elliptic flow and correlation measurements as constraints to establish the transport properties of hot and dense QCD matter is discussed. Measured Two- and three-particle correlation functions give initial hints for a “sonic boom”. Elliptic flow measurements give the estimates \( c_s \sim 0.35 \) and \( \eta/s \sim 0.1 \) for the sound speed and viscosity to entropy ratio.

1. Introduction

The Big Bang Model is a widely accepted theory for the origin and evolution of our universe. It postulates that \( \sim 12 - 14 \) billion years ago, a hot and dense plasma of quarks and gluons (QGP) was produced a few microseconds after the “big bang”. A pervading uniform glow of cold cosmic microwave background provides an unequivocal signature for the subsequent expansion from this hot and dense state to the vast and significantly cooler cosmos we currently inhabit [1].

Recent experiments at Brookhaven’s Relativistic Heavy Ion Collider (RHIC), give evidence for the creation of locally equilibrated hot and dense QCD matter in a “little bang” initiated in relativistic Au+Au collisions [2]. A short time after this bang (\( \sim 1 \text{fm}/c \)), the energy density is estimated to be \( \simeq 5.4 \text{ GeV/fm}^3 \) [2] – a value significantly larger than the \( \sim 1 \text{ GeV/fm}^3 \) required for the transition from low-temperature hadronic matter to the high-temperature QGP phase of QCD [3]. The subsequent expansion and ultimate hadronization of this high energy density matter, results in the emission of particles which signal its thermodynamic and dynamical properties.

An important challenge is to develop robust experimental constraints for these properties. This contribution discusses the role of both elliptic flow and hot QCD “sonic boom” measurements as constraints.

2. Sonic Booms

Objects moving at supersonic speeds in a medium create a wake behind the shock front they create. The familiar sonic boom from supersonic jets is the audible component of such a Mach cone produced in air. Similar Mach cones were initially predicted to occur in cold nuclear matter via bombardment of a heavy target nucleus with a light relativistic projectile [4]. A schematic illustration for the generation of such a shock front is shown in Fig. 1. Matter flow is normal to the shock front which subtends a Mach angle given
by the ratio $v/c_s$, where $v$ and $c_s$ are the projectile and sound velocities.

An extensive search at the BEVALAC concluded that cold nuclear matter was too dilute and dissipative to sustain the propagation of such a shock front.

### 2.1. Sonic Booms in Hot and Dense QCD Matter

A confluence of recent RHIC measurements have generated much interest in the search for Mach cones in high energy density QCD matter [5]: (i) Hot and dense QCD matter is produced well above the temperature required for QGP production. (ii) Elliptic flow measurements validate the predictions of perfect fluid hydrodynamics [7, 8] and do not show the expected suppression of flow due to the shear viscosity predicted by weak-coupling transport calculations. In fact, only a rather small value for the viscosity to entropy ratio $\eta/s \sim 0.1$, can be accommodated by the data (see estimate below and Refs. [9] and [10]). This has been interpreted as evidence that the QGP created in the early phase of RHIC collisions is more strongly coupled than expected [11]. (iii) Jet suppression measurements [6] indicate that the hot and dense QCD matter is almost opaque to high energy partons which deposit a substantial fraction of their energy into the matter.

Thus, the expectation is that the jet energy dumped into the strongly coupled plasma could survive as a coherent radiation of sound waves leading to a Mach cone (sonic boom) with Mach angle $\cos \theta_M = v_j/c_s$ as illustrated in Fig. 2 [5]. Here, $v_j$ is the jet velocity and the direction of matter flow is normal to the shock front. An important point to be made here is that the detection of a sonic boom naturally leads to important constraints for the viscosity and sound speed of hot QCD matter.

Two- and three-particle correlation function measurements provide an excellent probe for the sonic boom [12]. Background subtracted $\Delta\phi$ correlation functions from central Au+Au collisions are shown in Figs. 3 and 4 for trigger and associated particle $p_T$s as indicated. In contrast to p+p and d+Au collisions which show an away-side jet peak at $\Delta\phi = 180^\circ$ (cf. Fig. 4), the correlation functions for central Au+Au collisions show a broad minimum (cf. Fig. 3) at this angle. An apparent maximum in the distribution for the away-side jet corresponding to an estimated Mach angle (see red arrows) has been interpreted as initial evidence for a sonic boom in hot QCD matter [5].
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An issue which complicates the Mach cone interpretation of the Au+Au results in Figs. 3 and 4 is the possibility that the away-side jet might undergo large deflections due to interactions between the jet and the expanding system [13]. Such deflections can give rise to a $\Delta\phi$ correlation function similar to the one expected from a Mach cone. To resolve this ambiguity, state-of-the-art three-particle correlation function techniques have been developed [12].

Figure 5b shows a full three-particle correlation function (no background subtraction) obtained by combining a high $p_T$ particle with two associated low $p_T$ particles in a frame which approximates the actual jet frame. This frame of reference is illustrated in Fig. 5a. The high $p_T$ trigger particle ($p_1$) is coincident with the z-axis. The polar angle $\theta^*$, and the azimuthal angle difference $\Delta\phi^*$ for the associated low $p_T$ particles ($p_2n$ and $p_3n$ for same (near) side jet; $p_2-a$ and $p_3-a$ for the away-side jet) are used as correlation variables. In this polar ($\theta^*, \Delta\phi^*$) representation, the near-side jet correlations are expected at the center of the correlation surface; after background subtraction, a $\Delta\phi^*$ ring at $\theta^* = v_j/c_s$ (ie. the Mach angle) would signal the correlations from an away-side Mach cone.

Figure 5b show sizable correlations in $\Delta\phi^*$ for $\theta^* \sim 120^\circ$, albeit with acceptance losses especially in the region about ($\Delta\phi^* \sim 180^\circ$). These correlations are tantalizingly suggestive. However, the answer to the question as to whether or not they are due to a Mach cone, must await the results of accurate background subtraction. Suffice to say, initial indications are quite encouraging.

3. Transport Properties from $v_2$ Measurements

As mentioned earlier, elliptic flow measurements [7, 8] validate the predictions of perfect fluid hydrodynamics for the scaling of the elliptic flow coefficient $v_2$ with eccentricity

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1In a recent presentation at the Hard Probes meeting, the STAR collaboration has also indicated a significant three-particle correlation yield after background subtraction.


Figure 5. (Color online) (a) Schematic diagram of the coordinate frame used for three-particle correlation functions. The leading (high $p_T$ particle) is assumed to be the $z$ axis. The polar coordinates $\theta^*$, $\Delta \phi^*$ of the associated particles are indicated. (b) Full $\theta^*$, $\Delta \phi^*$ three-particle correlation surface for charged hadrons detected in central (0-5%) Au+Au collisions within the PHENIX acceptance.

$\varepsilon$, system size and transverse kinetic energy $KE_T$ [14, 15, 16]; they also indicate the predictions of quark number ($n_q$) scaling [17], suggesting that quark-like degrees of freedom are pertinent when elliptic flow develops.

Figure 6 shows scaled $v_2$ values for Cu+Cu and Au+Au collisions; they are clearly independent of the colliding system size and show essentially perfect $\varepsilon$ scaling for a broad range of centralities. Such scalings are in accord with the scale invariance of perfect fluid hydrodynamics [18, 15] and can be used to constrain the sound speed [7, 8].

Figure 7 shows a plot of $v_2/n_q\varepsilon$ vs $KE_T/n_q$; it demonstrates that the relatively “complicated” dependence of $v_2$ on centrality, transverse momentum, particle type and quark number can be scaled to a single function [7, 8]. The dashed-dotted curve indicates a fit to these data.

3.1. Estimating $\eta/s$

The viscosity to entropy ratio can be expressed as:

$$\eta/s \sim T\lambda_f c_s,$$

where $T$ is the temperature, $\lambda_f$ is the mean free path and $c_s$ is the sound speed in the matter. The temperature $T = 165 \pm 3\text{ MeV}$ is constrained via a fit to the data in Fig. 7 with the fit function $I_1(w)/I_0(w)$, where $w = KE_T/2T$ and $I_1(w)$ and $I_0(w)$ are Bessel functions [16]. For $c_s$, the estimate $c_s = 0.35 \pm 0.05$, given in Refs. [7] and [8], is used. An estimate $\lambda_f = 0.3 \pm 0.03\text{ fm}$, is obtained from the on-shell transport model simulations.
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Figure 6. (Color online) $v_2(centrality, p_T)$ divided by 3 times the $p_T$-integrated value $v_2(centrality)$, for Au+Au and Cu+Cu collisions.

Figure 7. (Color online) $v_2/\varepsilon n_q$ vs $KE_T/n_q$ for several identified particle species for minimum bias Au+Au collisions.

of Xu and Greiner [19]. This parton cascade model includes pQCD $2 \leftrightarrow 2$ and $2 \leftrightarrow 3$ scatterings.

With these values for $\lambda_f$, $T$ and $c_s$ one obtains the estimate $\eta/s \sim 0.09 \pm 0.015$ which is in good agreement with the estimates of Teaney and Gavin [9, 10]. It is also close to the lower bound of $\eta/s = 1/4\pi$, reached in the strong coupling limit of certain gauge theories [20].

4. Summary

The development of robust experimental constraints for the thermodynamic and transport properties of the strongly coupled plasma believed to be produced in Au+Au collisions at RHIC, constitutes a major current challenge. Elliptic flow measurements provide an initial set of constraints for the estimates $c_s \sim 0.35$ and $\eta/s \sim 0.1$. Quantitative confirmation of an initial hint for a hot QCD “sonic boom” from two- and three-particle correlation functions, will undoubtedly provide invaluable additional constraints.

REFERENCES

1. P.J.E. Peebles, D.N. Schramm, E.L. Turner and R.G. Kron, Nature, 352, 769 (1991).
2. Adcox, K. and others, Nucl. Phys. A757, 184 (2005).
3. F. Karsch, Nucl. Phys. A698, 199 (2002).
4. W. Scheid, H. Muller, and W. Greiner, PRL 32, 741 (1974); D.H.Rischke, H.Stocker and W.Greiner, Phys.Rev. D42, 2283, (1990).
5. H. Stöcker, nucl-th/0406018; J. Casalderrey-Solana et al, hep-ph/0411315; B. Muller et al, hep-ph/0503158 T. Renk et al, hep-ph/0509036
6. K. Adcox et al (PHENIX), PRL 88, 022301, 2002; C. Adler et al (STAR) PRL 89, 202301 (2002)
7. M. Issah, and A. Taranenko (PHENIX), nucl-ex/0604011 (2006).
8. A. Adare et al (PHENIX), nucl-ex/0608033 (2006).
9. D. Teaney, Phys. Rev. C68, 034913 (2003).
10. Sean Gavin and Mohamed Abdel-Aziz, nucl-th/0606061 (2006).
11. E. Shuryak, Nucl. Phys. A750, 64 (2005); T, Hirano, and M. Gyulassy, Nucl. Phys. A769, 71 (2006).
12. N. N. Ajitanand (PHENIX), nucl-ex/0510040 (2005); S.S Adler et al (PHENIX), Phys. Rev. Lett. 97, 052321, (2006).
13. S. N. Armesto, C. A. Salgado and Urs Wiedemann, Phys. Rev. C72, 064910 (2005).
14. M. Csanád, et al, nucl-th/0512078 (2005).
15. R. S. Bhalerao et al, Phys. Lett. B627, 49 (2005).
16. M. Csanad et al, nucl-th/0605044 (2006).
17. S. A. Voloshin, Nucl. Phys. A715, 379 (2003); nucl-ex/0210014
18. Roy A. Lacey, nucl-ex/0510029 (2005).
19. Zhe Xu and Carsten Greiner, Phys. Rev. C71, 064901 (2005).
20. P. Kovtun, D. T. Son, and A. O. Starinets, Phys. Rev. Lett. 94, 111601 (2005).